OPTIMIZATION OF SUBMERGED ARC WELDING (SAW) AND GAS TUNGSTEN ARC WELDING (GTAW) PROCESSES AND ACHIEVING ENHANCE EXCELLENCE OF WELDS QUALITY

BY

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عمادة الدراسات العليا
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بسم الله الرحمن الرحيم

DEDICATED TO MY BELOVED PARENTS, WIFE AND TEACHERS WHOSE CONSTANT PRAYERS, SACRIFICE AND INSPIRATION LED TO THIS WONDERFUL ACCOMPLISHMENT

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LIST OF ABBREVIATIONS

AC	:	Alternate Current
AISI	:	American Institute of Steel and Iron
ANOVA	:	Analyses of Variance
API	:	American Petroleum Institute
ASME	:	American Society of Mechanical Engineers
ASTM	:	American Society of Testing Materials
BM	:	Base Metal
CCD	:	Central Composite Design
CE	:	Carbon Equivalent
DA	:	Desirability Analyses
DC	:	Direct Current
DCEN	:	Direct Current Electrode Negative
DCEP	:	Direct Current Electrode Positive
Df	:	Degree of Freedom
DF	:	Desirability Function
DOE	:	Design of Experiment

EV	:	Essential Variable
FCAW	:	Flux Core Arc Welding
GMAW	:	Gas Metal Arc Welding
GTAW	:	Gas Tungsten Arc Welding
HAZ	:	Heat Affected Zone
LOF	:	Lack of Fusion
LTB	:	Largest the Best
MPa	:	Mega Pascal
NDT	:	Non Destructive Testing
NEV	:	Non Essential Variable
NTB	:	Nominal the Best
OFM	:	Orthogonal Factorial Method
PQR	:	Procedure Qualification Record
PREN	:	Pitting Resistance Equivalent Number
PWHT	:	Post Weld Heat Treatment
SAW	:	Submerge Arc Welding
SEV	:	Supplement Essential Variable

SMAW	**:**	Shield Metal Arc Welding
S/N	**:**	Signal to Noise
STB	**:**	Smaller the Best
UTS	**:**	Ultimate Tensile Strength
WPS	**:**	Welding Procedure Specification
WQT	**:**	Welder Qualification Test
WM	**:**	Weld Metal

ABSTRACT

Full Name : Muhammad Asad Ahmad

Thesis Title : OPTIMIZATION OF SUBMERGED ARC WELDING (SAW) AND GAS TUNGSTEN ARC WELDING (GTAW) PROCESSES AND ACHIEVING ENHANCE EXCELLENCE OF WELDS QUALITY

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Submerged-Arc-Welding (SAW) and Gas-Tungsten-Arc-Welding (GTAW) are widely used welding processes which are being utilized for fabrication/manufacturing industry due to their good weld quality. SAW is an automatic (semi/fully) processbut GTAW is mostly used as a manual process. Productivity and quality is the main concern in many manufacturing and industrial welding applications. Therefore, selection of a welding process and its variables/parameters without sacrificing weld quality with respect to productivity and its quality is very important. SAW process is that versatile welding process which becomes the first choice under these circumstances therefore SAW process is famous for its usage in heavy industry because of its high weld productivity. Although manual GTAW process has less productivity yet still having very good weld quality especially for root passes, small thicknesses and stainless steel. There are many variables which affect both processes. In this thesis, important controllable factors of these processes are focused like current, voltage, travel speed, gas flow rate in GTAW, and heat input etc., and then effects of these are studied on other responses like ultimate tensile strength (UTS), weld hardness, deposition rate, bead width and reinforcement. At last combination of these factors is also found for the best weld having high weld strength and deposition rate, minimum specified hardness, moderate bead width and

reinforcement etc., by using Taguchi S/N ratio analyses and desirability function analysis (DA). Most optimized predicted conditions for the given weld material and process are experimentally validated and results of the best weld quality features are found to be in excellent agreement with the models based values.

ملخص الرسالة

الاسم الكامل: محمد اسد احمد

عنوان الرسالة:تحسين عمليات اللحام بالقوس الغاطسة (SAW) وعمليات اللحام بالقوس بالتنغستن (GTAW) باستخدام تصميم التجارب وتقنيات التحليل الإحصائي

التخصص: هندسة ميكانيكي

تاريخ الدرجة العلمية: مايو 2019

تستخدم عمليات اللحام بالقوس المغمور (SAW) واللحام بالغاز بالتنغستن (GTAW) على نطاق واسع في عمليات اللحام التي يتم استخدامها في الصناعة التحويلية / التصنيع بسبب جودة اللحام الجيدة. SAW هي عملية تلقائية (شبه / كاملة) ولكن يتم استخدام GTAW في الغالب كعملية يدوية. الإنتاجية والجودة هي الشاغل الرئيسي في العديد من تطبيقات اللحام الصناعي والصناعي. لذلك ، يعد اختيار عملية اللحام ومتغيراتها / معلماتها دون التضحية بجودة اللحام فيما يتعلق بالإنتاجية وجودتها مهمة للغاية. عملية SAW هي عملية اللحام متعددة الاستخدامات التي أصبحت الخيار الأول في ظل هذه الظروف ، لذلك تشتهر عملية SAW باستخدامها في الصناعات الثقيلة بسبب إنتاجيتها العالية للحام

على الرغم من أن عملية GTAW اليدوية لديها إنتاجية أقل ، إلا أنها لا تزال تتمتع بجودة لحام جيدة للغاية خاصة بالنسبة لتمريرات الجذر ، والسماكات الصغيرة والفولاذ المقاوم للصدأ. هناك العديد من المتغيرات التي تؤثر على كلتا العمليتين. ركزت في هذه الأطروحة على عوامل مهمة يمكن السيطرة عليها في هذه العمليات مثل التيار والجهد وسرعة السفر ومعدل تدفق الغاز في GTAW وإدخال الحرارة وما إلى ذلك ، ثم درست آثارها على استجابات أخرى مثل قوة الشد القصوى (UTS) ، صلابة اللحام ، معدل الترسيب ، عرض حبة والتعزيز. لقد وجدت أيضًا مزيجًا من هذه العوامل لأفضل اللحام ذي قوة اللحام العالية ومعدل الترسيب والحد الأدنى من الصلابة المحددة وعرض الخرزة المعتدل والتعزيز وما إلى ذلك باستخدام تحليلات نسبة تاغوتشي S / N ووظيفة الرغبة (DA) .يتم التحقق من صحة معظم الظروف المتوقعة المُحسَّنة لمواد وعملية اللحام المحددة وتجربة نتائج أفضل ميزات جودة اللحام تتفق بشكل ممتاز مع القيم القائمة على النماذج.

CHAPTER 1

INTRODUCTION TO WELDING

Joining of metals is very useful concept which is being utilized since Bronze Age and then gradual advancement gave rise to development of modern welding. Concept of welding was being created once man learnt how to deal with metals. But history starts from Bronze age before 3000 BC where metals joining process were done through soldering and press lap joint method and the joining process was done mostly only for Silver and Gold . Then man learned forge welded iron in Iron Age and then forge welding by blacksmith in Middle age. But 19^{th} and 20^{th} centuries were the time when modern arc welding had its practical beginning and then lot of research work and development from different manufacturers gradually open new horizons to reshape the welding technology because before World War I and II welding had its limited manufacturing applications. The first utilization of arc covered under the bed of granular flux was started during II world war and became the most popular and famous process for T34 tanks fabrication [1]. Then gradual research helped to introduce new welding processes and therefore as a result there is large list of welding processes having different methodologies and applications to utilize in different fields. Gus Tungsten Arc Welding (GTAW) and Submerged Arc Welding (SAW) are also among those processes which are increasingly used in modern era in the fields of fabrication, manufacturing and construction.

1.1 GAS TUNGSTEN ARC WELDING

Gas Tungsten Arc welding (GTAW) is also known as Helium Arc or tungsten inert gas welding. This process was initially developed in 1930s to weld magnesium. Russel Meredith was the one who developed this process by using inert gas of helium and used tungsten as an electrode to fuse magnesium [2]. In fact this process replaced riveting and helped to joined aircraft components of Al & Mg by welding through this process. The HeliArc welding has continued to this day with many refinements and name changes, but with no change in the fundamentals demonstrated by Meredith developed in the aircraft industry. Direct current electrode negative with Tungsten electrode initiate stable arc and can produce excellent weld. Since from invention number of improvements were made in this process including constant current power source, water or gas cooled torches were developed, and tungsten electrode was alloyed with some active elements to improve and made stable emissivity. Gases and their blends were introduced to improve performance of this process [3].

Figure 1 GTAW Process [4]

1.1.1 PRINCIPLE OF OPERATION

In this process non consumable electrode of tungsten is used to initiate an arc and to melt the metals. Electrode is held in a torch which is also connected to a gas source to provide gas for shielding. Contact tube which is actually water cool copper tube which connect electrode with power source and provide cooling to prevent over-heating. Whereas work piece is connected to power source with another cable. Shielding gas moves through Torch in a nozzle which is directed towards the weld pool area. Here shielding is much better than SMAW because of two reason, one is use of an inert gas like argon or helium and second is that gas nozzle is directed towards weld area. Sometime non inert gas also used in small quantity so GTAW looks more appropriate name for this process. For thicker sections when filler rod is used then it can be added manually or automatically into the arc. The non-consumable electrodes used in GTAW are composed of tungsten or alloys of tungsten [5].

The most common electrode is a 2% ThO2-W alloy (EWTh-2). This material has excellent operating characteristics and good stability. Thoria is radioactive, so care must be taken when sharpening electrodes not to inhale metal dust. The grindings are considered hazardous waste in some states, and disposal may be subject to environmental regulations. Lanthaniated (EWLa-1) and yttriated tungsten electrodes have the best starting characteristics in that an arc can be started and maintained at a lower voltage. Ceriated tungsten (EWCe-2) is only slightly better than the thoriated tungsten with respect to arc starting and melt-off rate. Any of the aforementioned electrodes produce acceptable welds. The easy starting of the lanthaniated electrode is a result of the lower work function which allows it to emit electrodes readily at a lower voltage. Pure tungsten is used primarily in arc welding and has the highest consumption rate. Alloys of zirconium are also used.

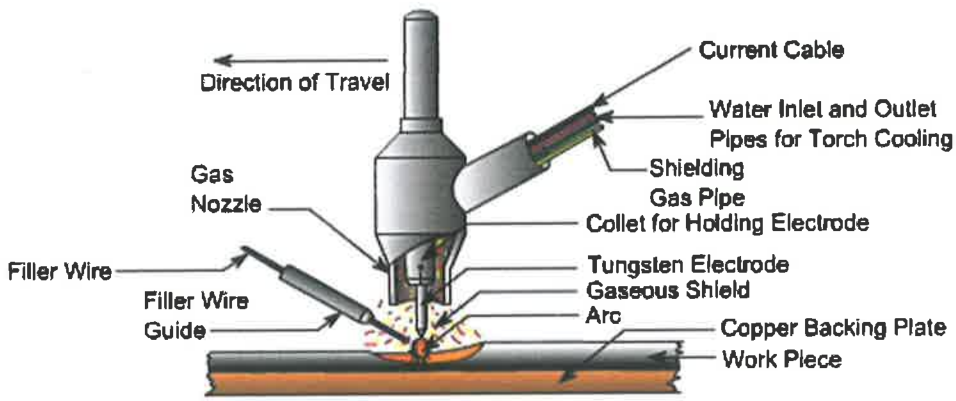


Figure 2 Schematic diagram of GTAW [6]

GTAW is a process which is suitable for most of the materials. Low & high carbon steel, stainless steel, cast iron, heat resistant alloys, Aluminum, Copper and Magnesium alloys and refractory metals are easily welded with GTAW process.

Shielding gas provides an inert atmosphere that prevents oxygen contamination of the weld pool and the tungsten electrode. Typical gases used for shielding are

- Argon (heavier than air, low cost, adequate penetration (more attractive)
- Helium (lighter than air, not provide adequate shielding, greater penetration, thick material)
- Argon-helium blend

Shielding gases protect tungsten from oxidation which will tend to melt the non-consumable part. Adding 2% O2 will increase fluidity and 1-8% H2 can be used for stainless steel and Ni based alloy to increase heat energy & reducing agent.

1.2 SUBMERGE ARC WELDING

The first utilization of arc covered under the bed of granular flux was started during II world war and became most popular and famous process for T34 tanks fabrication. Then gradual improvements in this process made this very useful for heavy manufacturing industries. Then gradual improvements in this process made this useful for heavy thicknesses and more production. For last fifteen to twenty years this process is increasingly used due to good weld quality and good productivity [1]. Currently Submerged arc welding is adaptable to both semiautomatic and fully automatic operation, although the latter, because of its inherent advantages, is more popular in fabrication and manufacturing industry

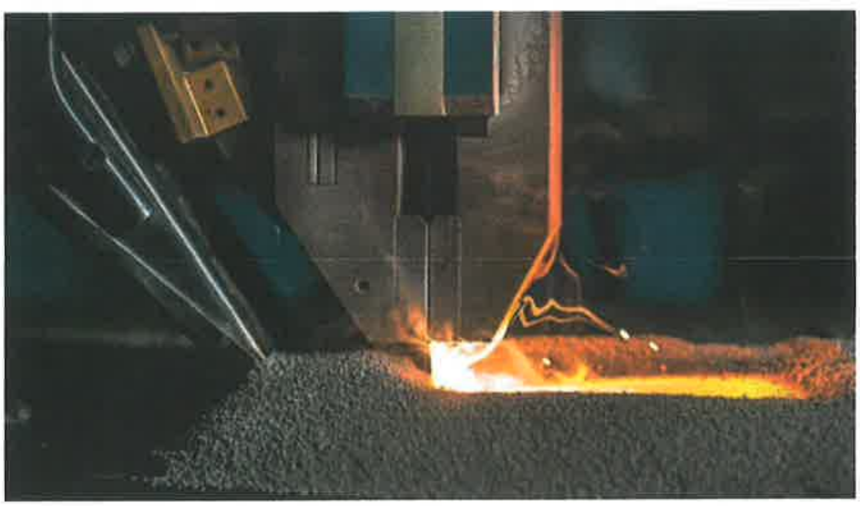


Figure 3 SAW Process [7]

1.2.1 PRINCIPLE OF OPERATION

In submerged arc welding drive rolls are used to provide continuous feed of electrode wire. Then layer of granular flux is being deposited in front of an arc and deep enough to prevent flash through. Here DCEP (reverse polarity), DCEN (straight polarity) or AC can be used.

After welding is completed and the weld metal has solidified, the unfused flux and slag are removed. The unfused flux may be screened and reused. The solidified slag may be collected, crushed, resized, and blended back into new flux. Recrushed slag and blends of recrushed slag with unused (virgin) flux are chemically different from new flux. Blends of recrushed slag may be classified as a welding flux, but cannot be considered the same as the original virgin flux [8].

Submerged arc welding is adaptable to both semiautomatic and fully automatic operation, although the latter, because of its inherent advantages, is more popular. In semiautomatic welding, the welding operator controls the travel speed & direction, and weld placement also. A semiautomatic welding gun is designed to transport the flux and wire to the operator, who welds by dragging the gun along the weld joint. Semiautomatic electrode diameters are usually less than 2.4 mm (3/32in.) to provide sufficient flexibility and feed ability in the gun assembly. Manually guiding the gun over the joint requires skill because the joint is obscured from view by the flux layer.

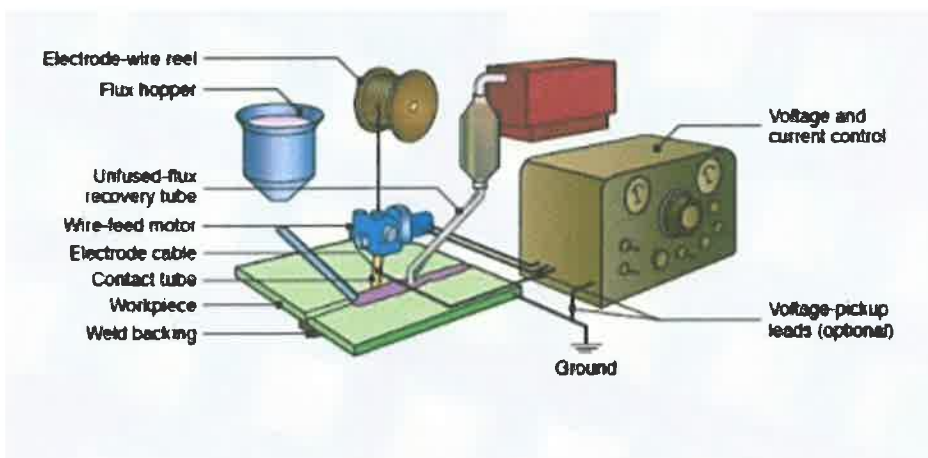


Figure 4 Schematic Diagram of SAW [9]

In automatic welding, mechanical means are used to control travel speed and direction. Flux may be automatically deposited in front of the arc, while vacuum recovery system is used behind the arc to pick unfused flux. To increase deposition rate or welding speed, more than one wire can be fed simultaneously into the same weld pool. For example, in the twin arc process, two electrodes are fed into the same weld pool while sharing a common power source and contact tip. In tandem arc SAW, multiple electrodes are arranged with one in front of the other. Each electrode has an independent power supply and contact tip. The spacing, configuration, and electrical nature of the electrodes may be arranged to optimize welding speed and bead shape. Bead shape, penetration depth and chemical composition of deposited weld metal all are affected by parameters like welding current & voltage and travel speed. In semi-automatic operator is not able to see the weld pool so greatly dependable on parameters settings. Either AC or DC current along with single wire can be used to operate SAW. Common variants are:

- twin or multiple wires
- single wire some time with addition of hot or cold wire
- Addition of metal powder
- Tubular type wire

Here all these increase weld deposition and/or travel speeds so improve productivity. A two or three bead per layer techniques are also used as narrow gap process variant. Granular fluxes which are used in SAW contains fusible minerals like oxides of Mn, Si, Ti, Al, Ca, Zr, Mg and other compounds like $CaF2$. Then flux is formulated to become compatible for electrode wire so that combination of both wire and flux would give desire mechanical properties. Because fluxes react with weld pool to give desire chemical and mechanical propeties. Fluxes are called active if they add Mn & Si to weld because both are influenced by arc voltage and welding current. There are two types of SAW fluxes which are:

- **Bonded fluxes** – here ingredients are dried and bonded with low melting point compounds sodium silicate. Most of them also contain de oxidizer to prevent porosity. These are also effective to use over mill scale or rusty area.
- **Fused fluxes** – here ingredients are mixed and melted in a furnace to produce chemically homogenous form and then cooled to form a desire product form. Main advantages of these fluxes are; smooth and stable arcs with high welding current and consistent properties of weld metal.

1.3 LITERATURE REVIEW ON SAW AND GTAW

Research in welding technology was already started after the World War I. since GTAW is among those processes which were introduced in earlier stage of welding therefore most of the research work at that stage was done in the improvement of this process. Submerged arc process was introduced in initial form after the World War II but most of the development in this process was seen in the 60's and 70's era and after that. Following paragraphs provide recent research in the field of gas tungsten and specially submerged arc welding processes.

GTAW process parameters correlation for weld pool formation was studied by Min Jou et.al. [10]. He found that welding speed effect was ignorable at low arc current whereas at high arc current, heat distribution decreased when weld speed was increased.

Srirangan and Paulraj [11] tried multi response optimization of process parameters. But initially they worked on TIG welding. Material used for this study was incoloy 800HT and technique used for optimization was Taguchi grey relational analysis. Y S Yegaie, A Kermanpur and M Shamanian [12] developed 3D thermos mechanical simulation model to find temperature and residual stresses during GTAW welding. Results of experiments were validated against experimental measures for released strain and temperature in welded plates. Process and other variables like heat input, pipe dia. and water flow rate considered for investigation. Finally they concluded that high temperature region limited to vicinity of heat source and maximum temperature of sample was much lower than that of conventional GTAW process.

K S Pujari, D V Patil and M. Gurunath [13] worked on optimization of AC pulse GTAW process parameters to control geometry of weld pool for AA 7075-T6 Al alloy. They focused on weld pool because this affect the mechanical properties of weld joint. Aluminium alloy was selected for experiment because for Al and Al alloys GTAW is the process mostly used. Taguchi, utility concept and ANOVA analyses were used for experimental work.

Optimization of activated TIG welding of 304L austenitic stainless steel was performed by S C Bodkhe, and D R Dolas [14]. Main focus of their study was to achieve higher penetration depth. They selected current, voltage, arc gap and weld speed were selected as process parameters and then optimized by using central composite design of response surface methodology and ANOVA analyses were also performed. In order to predict maximum depth of penetration they developed linear regression equation and then desirability approach used for numerical optimization.

H K Bhadeshia et.al, and J. Bauer [15] [16] in 1989 studied the microstructure of SAW deposits for high strength steels. Microstructure which was mixture of acicular ferrite, bainite and martensite. Levels of strength and toughness properties were presented along with ferrite and pearlite structure.

CCT diagram for low carbon steel was evaluated by R W Fonda [17] whereas microstructure and wear properties of alloy material Fe-Mn-Cr-Mo-V were studied by Shaun Ping [18]. Increase in austenite was due to increase in current and decrease in travel speed. Phase balanced microstructure was proposed by Henrie Sieurin [19] after studying austenitic reformation in HAZ of DSS 2205 material.

Multiple thermal cycles of HAZ for crMoV steels was studied by D Wojnowski [20]. Inter-critical temperature at HAZ was found 790C. Effect of coarse initial grain size on microstructure weld and HAZ metal was studied by M Eroglu [21]. Increase in thickness will increase heat input which in turn will increase toughness of HAZ.

Effect of process parameters on microstructure and weld penetration was investigated by C S Chai [22]. Gunaraj [23] study the effect of process variables and heat input by developing equations. He concluded that heat input and wire feed have increasing effect on HAZ characteristics. Yayla et.al. [24] Studied welding parameters effects on mechanical properties of HY 80 steel welds.

ER Dhas and S Kumana [25], professors of NI University India, used non-traditional method to optimize SAW process. They used welding current, speed, arc voltage and electrode stick out length to study weld bead because these factors greatly effect on weld bead. Due to non-linear relationship of these factors they used non-traditional trial and error method on mild steel plate for their experiment. Taguchi design and regression analyses were used to develop a input-output relationship then by using that relationship attempt was made to minimize bead width. They utilized genetic algorithm and particle swarm optimization to find optimal parameters.

Siddharth Choudhary and Rohit Shandley [26] optimized agglomerated fluxes of SAW process. They worked on to find effect of different types of agglomerated fluxes on hardness and impact strength for low carbon steel plates. Several combination of CaO, Al2O3, TiO2 and MgO were developed by using Taguchi L8 orthogonal array with couple of voltage ranges and developed a n optimal combination of these for the desired hardness and good impact strength.

M A Moradpour, S H Hashemi and k Khalili [27] performed multi objective optimization of SAW welding for API steel plate material of X65. Their main object was to control weld bead for good weld quality in larger diameter gas transmission pipelines. They proposed a new approach for beast bead geometry after process parameters optimization by using fuzzy logic and non-dominated sorting genetic algorithm-II techniques. Fuzzy model was used to predict weld bead geometry and then parameters were optimized to achieve the desired values of convexity and penetration indexes simultaneously using NSGA-II approach.

Effect of heat generation on SAW welding of mild steel plate at zero degree temperature of plate was studied by Ajay Biswas and Abhijit Bhowmik [28]. Experiment was carried out on heavy duty mild steel of IS 2062 grade B material while plate material was zero centigrade. Taguchi design was used for experiment run and lab review software was used for analyses. Then bead geometry attributes were measured and observed. They concluded that it is possible to weld using SAW process when material temperature is zero centigrade.

M Satheesh, J Edwin, S Kumar [29] analyzed the weld parameters of SAW process on Micro hardness of SA 516 Gr. 70 steel material. By using multiple regression methods were used to study and predict the relationships between process parameters and micro hardness. Interaction effects of process variables on micro hardness and presented in graphical form.

Weld bead characteristics during submerged arc welding of AISI 1023 steel were studied by A Choudhary, M kumar and Deepak R [30]. They used fractional factorial method design to analyze effect of direct and indirect parameters like voltage, wire feed rate, flux condition and plate thickness on weld bead on AISI steel plates. Main and interaction effect of parameters are studied on responses and then develop mathematical models for selective responses. They utilized genetic and Jaya algorithm for analyses.

How to control bending distortion for I-beams using submerged arc welding process was studied by Mohammed T H, Abdullah Al-Dwairi and Sinan F Obeidat [31]. They design this study to investigate bending distortion of I-beams fabricated from steel sheets. By using design of experiment technique and ANOVA analyses of variance effect of parameters on responses were studied in order to minimize bending distortion. They concluded that arc voltage and wire feed were the most important factors affecting the bending distortion whilst travel speed with minimum.

Ke Li, Zhisheng Wu, Yan Zhu and Cuirong Liu [32] studied metal transfer in submerged arc welding. For this study the molten metal at wire end in SAW was seen by using high speed video camera through preset tunnel. They found process stability very high at medium current but metal transfer was not easy. So they proposed three metal transfer modes with increasing current which were: repelled globular transfer without short circuit, flux wall guided transfer and flux wall guided transfer with short circuit. They conclude that arc always be there when short circuit is there with high current.

Dae W Cho and Degala Venkata [33] analysed the molten pool behavior by using flux wall guided metal transfer in low current submerged arc welding process. For this study they developed 3D numerical heat transfer and fkuid flow model to study the temperature distribution and molten pool behavior. For single wire low current SAW process they also suggested flux wall boundary model to simulate flux wall guided transfer. The same team then worked out to study molten pool behavior in the tandem submerged arc welding [34] where tandem process means usage of more than one wire. 3D numerical model was prepared for heat transfer and fluid flow to analyze the temperature profiles, velocity fields, weld pool size and shape in tandem submerged arc welding process.

Edwins and Jenkins [35] studied different methodologies which could be used for optimization. They also discussed different steps in general which were helpful for opting any optimization methodology. Their study was based on work of Ramasamy who worked on lot of research papers and concluded a path to perform optimization of any process as a result of that study. Therefore based on that they developed empirical formula to link factors and responses.

Holub and Dunovsky [36] studied different consumables for multilayer SAW welding to study their effect on mechanical properties like ductility and impact properties. They selected CrMoV heat resistant steel and as a new design used narrow gap plan for experiment. For their study they utilize different consumables then through testing found ductile and impact test properties of material after comparison. This work was related to CrMoV heat resistant steel with zero gap.

Aniruddah and Somnath [37] worked on selecting parameters to control bead width for the quality of weld and presented their results by using graphical techniques. Here parameters were optimized by graphical method and further results were also predicted by the same graphical methods.

P. Schaumann and M. Collmann [38] studied weld defects on fatigue life by using multilayer SAW process for large weld seams. They performed welding and then analyze for possible defects. After finding those defects they studied fatigue life of those seams with defects. Whereas Deshmukh and Venkatachalam [39] worked on penetration effect on cyclic fatigue life. With changing parameters they studied different penetration rates and based on that they analyzed effect of those penetration rated on cyclic fatigue life.

A Bharti and ND Pandey [40] studied effects of SAW parameters and fluxes on element transfer behavior and weld metal chemistry. They used different combinations of SAW variables with different fluxes to study elemnt transfer behavior and then its effect on weld metal combination.

YL Tarng and HL Tsai [41] worked on optimization of SAW parameters for hard facing process. Hard facing is a process where a harder and tougher material is applied on base metal to increase hardenability of that metal.

WH Yang and YS Tarng [42] used fuzzy logic technique in Taguchi method for optimization. Orthogonal array method was used for level settings of parameters and then fuzzy logic technique was used to optimize these parameters.

Lucia vera Barito OD, Jacobus Cornelis and team [43] worked out to find post weld heat treatment effect on ASTM A537 material by using SAW process. CH Chang, SC Jaung and YS tarng [44] used grey-based taguchi method to find SAW process parameters in hard facing.

Estrada Diaz. Lopez Hirata and Paniagua-Mercado [45] studied chemical and structural characterization of the crystalline phases in agglomerated fluxes for SAW process. By using different agglomerated fluxes SAW welding process performed on carbon steel and then different chemical and structural characterization analyses performed by using X-Ray spectroscopy.

S Datta and PK Pal [46] used grey based taguchi method for optimization of bead geometry in SAW process. Different variables and their values were studied to under their effect on bead width and finally concluded optimal values of parameters for moderate bead width. ANOVA analyses also performed to find variance in process.

V Gunurag and N Murugun [47] worked on optimization technique of Response surface methodology to predict weld bead in SAW process. SAW process parameters were optimized by developing a relation through equation by using RSM along with ANOVA analyses.

Therefore we can summarize major findings in research work which was carried out for last 15-20 years on both processes as follow:

- For GTAW recent researches are related to utilize this process for specific material or application

- 3D thermo mechanical simulation model was studied to find temperature and residual stresses
- AC pulse GTAW process parameters to control geometry of weld pool for Al alloys
- For SAW Weld bead geometry have been investigated and effects of SAW defects on fatigue life
- Microstructure with levels of strength and toughness properties were presented along with ferrite and pearlite structure.
- Heat input and wire feed were found to have increasing effect on HAZ structure
- Hard facing using SAW was studied to increase base metal hardenability
- Different type of fluxes were used to find their effect on mechanical properties

1.4 RESEARCH OBJECTIVE

The motivation of this research was to develop a frame work of maximizing the quality of weld by deploying design of experiments strategies and analyze the results to determine the robust parameters combination for highest desirable weld.

Standards are collaborative experience from customer voice having broader range of acceptable tolerances (acceptable zone from standard based tolerances). Within that window, there is scope of further improvement and enhancement of weld quality by identifying a tighten zone of tolerance. In order to achieve this following research objective is set;

Comprehensive optimization using different statistical approaches within constraints of welding standards to narrow down optimum region for process parameters within recommended window

This optimal region will result weld conditions of enhance best quality weld from set of standard base accepted conditions and circumstances. Then optimal responses and results shall be validated by performing actual run of welds.

1.5 METHODOLOGY

An overview of methodology used for attaining the objectives is as follow:

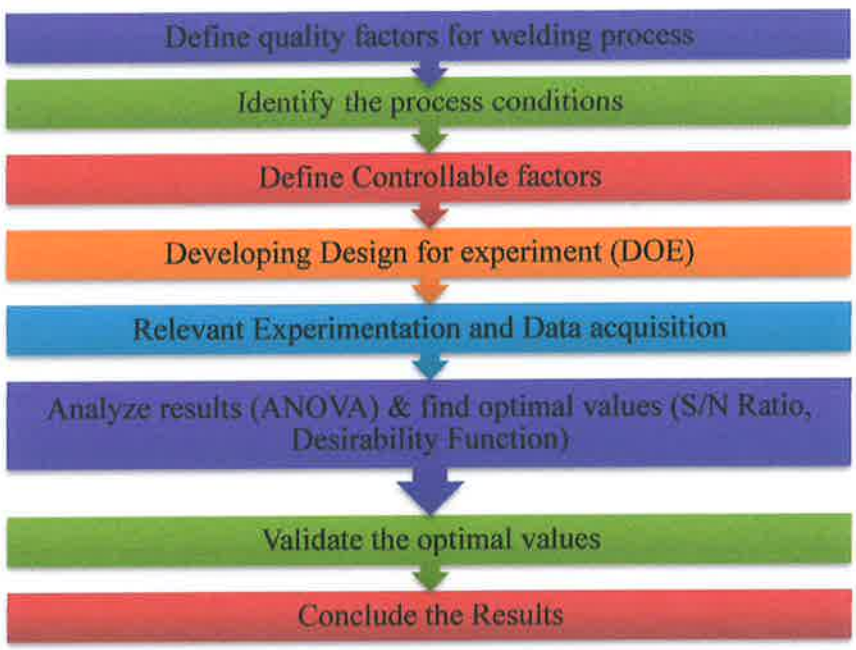


Figure 5 Design of Experiment (DOE) methodology

Conventional optimization process include large number of experiment trials whereas design of experiment (DOE) is economical way to conduct the experiments for the same purpose. Therefore I shall utilize DOE technique for this study.

It will begin with defining the objective of the experiment and selection of the factors for this study. Experimental design (which gives lay out for detailed experimental plan) will be chosen which will increase the information that will be obtained from amount of experiment efforts. My DOE study shall evolve the following steps:

- Defining the objective
- Selection of process variables (Factors)
- Selection of Experimental design
- Execution of that design
- Checking for the data
- Verification of its consistency with assumptions made during experiment
- Analyzing the results
- Presentation of the results

A sample schematic box for these welding processes is given below:

Figure 6 Schematic box diagram for welding process

Welding process parameters optimization is the key objective of this study. Design of taguchi orthogonal arrays are used to study process factors with given number of experiments and replication of that experiment data shall also be made to find the variation in the results.

Source of data is:

- Field experiments (study) results under consistent environment or process parameters of DOE (unpublished data)
- Experiments conducted by author in needed conditions at values specified by DOE

Base on experimental results, statistical performance i.e., signal to noise ratio (S/N Ratio) will be measured whereas S/N ratio is basically ratio of mean to Standard deviation. This S/N ratio is also utilized not only for ranking the factors according to their significance and also to find optimal values for various parameters and responses. Desirability function is also used to optimize the process responses and parameters. This study aim to disclose the application of design of experiment (central composite design and orthogonal factorial method) and desirability function for optimization of SAW/GTAW processes. By using these methodologies optimal values for selected controllable factors and responses will be found and then optimal responses values are validated by performing actual run of weld and then comparing the actual results with the calculated optimal values.

CHAPTER 2

PHYSICS OF WELDING

Physics of welding is always associated with different factors like power density, energy source intensity, and heat flow mechanism, fluid flow of molten metal, carbon equivalent and heat input. Different variables/parameters also play an important role to get the desire weld quality. All those variables which affect the weld quality may vary from process to process. Therefore by identifying and controlling those factors and variables a best weld of desire quality can be achieved.

Following are the important variables and factors which affect the physics of welding in SAW and GTAW welding.

2.1 IMPORTANT VARIABLES OF SAW

Following are those important variables of SAW process which can effect quality and characteristics of weld [8]:

- **Wire feed Speed:** wire feed speed and current are related directly with each other so increase in speed will increase current in the wire whereas density of current depends upon X-section of wire. So it means higher current density will cause higher penetration and fusion as well.
- **Voltage:** Both open circuit and arc voltages are important in SAW process because both effect on bead shape and penetration. The arc voltage also governs arc length beneath the flux layer and any change in arc length will change weld metal

composition due to change in element. By changing the composition mechanical properties will also change. So it is required to make sure tight connections for all cables being used in welding.

- **Electrode stick out:** The distance from weld head assembly to weld surface is electrode stick out. Electrode stick out affects amperage because power will be used to in resistance heating of wire. So electrode stick out value need to be mentioned in WPS.
- **Flux Depth:** Flux feed rate and feeding head to weld surface are used to control flux depth. This is required to fully cover the arc but optimum value because too high depth of flux also cause problems during welding.
- **Travel Speed:** travel speed is also an important variable in SAW because travel speed affects both on penetration as well as bead shape. In fully automatic process mechanized means are available to control but in semi-automatic welding operator is the one who controls the travel speed so for joints this should be given on WPS [48].

2.2 IMPORTANT VARIABLES OF GTAW

Following are the important variables of GTAW process which are considered for effective usage of a GTAW process [5].

- **Welding Current:** Welding current control penetration and also effects voltage. With fixed arc length voltage is proportional to current. Therefore to keep arc constant it is required to change voltage while adjusting current. DC or AC current can be used for this process that is a choice which depends upon type of material. DCEN gives good penetration and high speed with helium as an inert shielding gas whereas AC gives cathodic cleaning (Sputtering) and removes oxides from the surface during welding of Al or Mg with the portion of AC wave when electrode is positive w.r.t work piece. But here argon gets preference because helium is not useful for sputtering. Argon is also preferred for manual GTAW for both DC and AC powers.

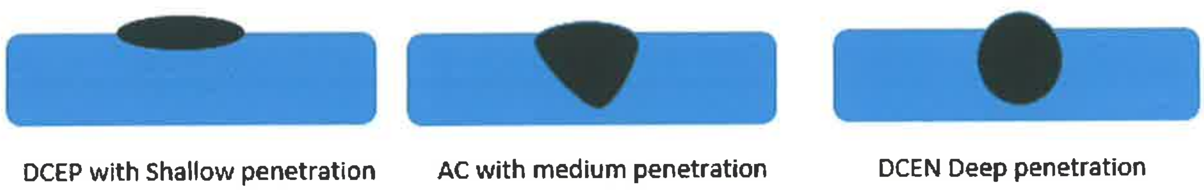


Figure 7 Penetration with AC/DC Polarities

- **Voltage:** Voltage can be changed with change in other variables. And is easy to measure. Other variables like current electrode and gas are predetermined so voltage controls the arc length which effects the width of weld pool. Therefore short arc length is always desired. But by using helium as shielding gas and DCEN power with high current electrode tip can be submerged below the surface of plate for deep penetration but with narrow bead at high speed. This is normally called buried arc.
- **Travel Speed:** Travel speed in GTAW controls width and penetration but mainly on width of weld bead. Travel speed is important because it effects cost and some application select this as an objective while other variables to control the weld quality. But in mechanized process travel speed remains constant and other variables like current, voltage are changed to produce a quality weld. So we can say travel speed is dependable variable which affects the weld shape and quality as well.

- **Wire Feed:** Wire feed plays a role in manual welding and the way filler metal is deposited to weld pool effects passes required and at the end appearance of the weld.
- **Gas Type & Flow Rate:** Normally two type of gases are used for GTAW process which are Argon & Helium and sometime Nitrogen and Hydrogen are also added. Argon is cheaper and has high density than air, it has lower ionization potential given a relatively shallow penetration. Whereas Helium is expensive and with lower density & high ionization potential giving higher penetration and hotter arc. Helium, because of its low density, must be used at higher flow rates than argon.
- **Slope in & Slope out:** Slope in and slope out is used to control the rise in current and its decay which helps to avoid crater pipes weld imperfection. These are available with GTAW machines.

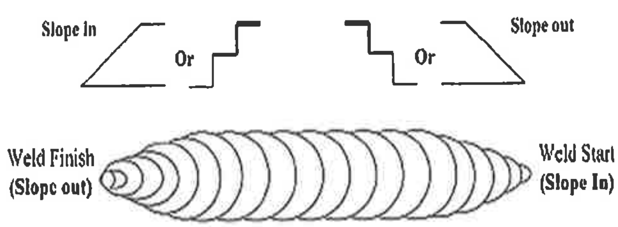


Figure 8 Slope in and Slope out [5]

- **Electrode Tip & Vertex Angle:** The tip of an electrode important because it effects to emit electrons. Different shapes are used for example with AC Zr-W electrode hemispherical shape is used. For DC welding Th-La-W electrodes end are ground to specific shape with specific vertex angle or with truncated end. A special grinder is used to grind and to make vertex angle. Too fine angle will cause melting of tip and sometime for AC power tip end is chamfered.

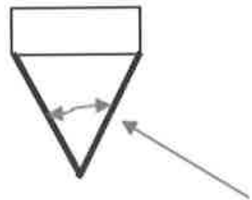


Figure 9 Tungsten electrode vertex angle

2.3 FACTORS AFFECTING PHYSICS OF WELDING

Some important factors affecting physics of welding are explained as follow:

2.3.1 HEAT FLOW MECHANISM IN FUSION WELDING

Heat flow has directly affected quality of a weld because it changes the physical state of weldment, transformation of metallurgical phase, distortion and thermal stresses created or residual stresses in the work piece [49].

Therefore Heat flow influences the weld joint conditions and it can also create a discontinuity due to sudden massive cooling and contraction between the weld and base metal area which may can cause brittle structure as a result of that situation. Heat flow is basically dependent on heat source which moves along the length of the weld and leaves it in transient thermal state. Heat source coincide with moving coordinates because it is continuously moves and therefore create weld metal (WM), heat affected zone (HAZ) and base metal (BM). This heat flow in thin material is 2D and in thick material it is 3D.

Heat flow in welding can be calculated by using Rosenthal equation with following assumptions:

- Heat flow is steady w.r.t moving heat source or temperature distribution does not change with time

- No convection and heat loss from weld surface
- Constant thermal properties

2D heat flow distribution and Rosenthal equation for calculation is given below:

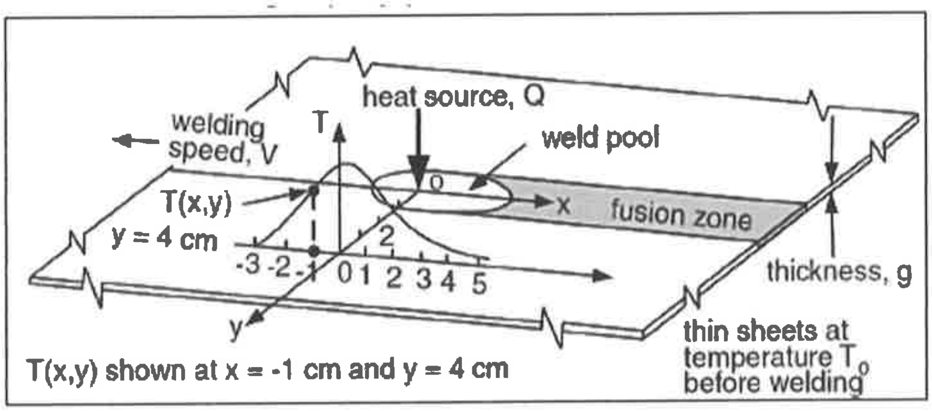


Figure 10 2D heat flow distribution [50]

Rosenthal Equation: $$\frac{2\pi(T-T0)kt}{Q} = exp\frac{Vx}{2\alpha}.Ko.\frac{Vr}{2\alpha} \qquad (2.1)$$

T = Temperature

T_0 = Surface temperature before welding

k, t = workpiece thermal conductivity and thickness

Q = heat transferred from source to work piece

V = travel speed

K_0 = Bessel function

α = workpiece thermal diffusivity

r = radial distance from origin

Similarly 3D temperature distribution in thick material along with Rosenthal heat calculation equation is as follow:

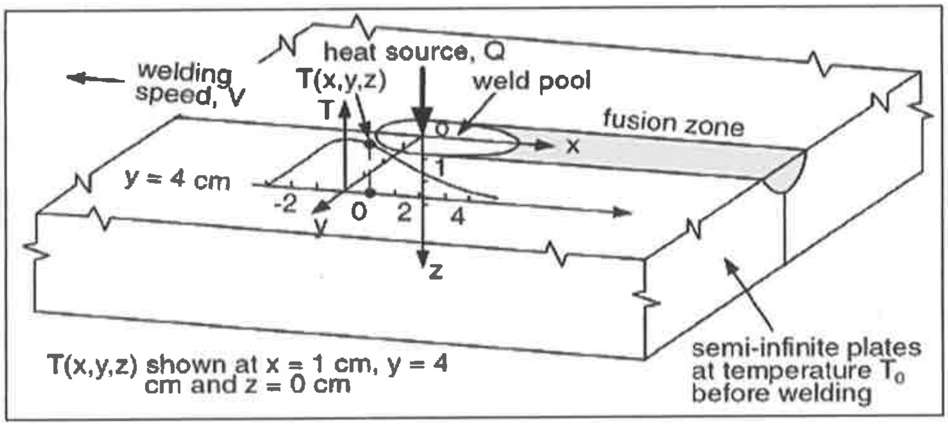


Figure 11 3D heat flow distribution [50]

Rosenthal Equation: $$\frac{2\pi(T-T0)kR}{Q} = \exp[\frac{-V(R-x)}{2\alpha}] \qquad (2.2)$$

Rate of cooling basically defines the micro structure of HAZ because control cooling causes desired structure but sudden cooling can cause brittle martensitic structure. In the same way thermal gradients control cooling and solidification rate at liquid-solid interface. Depth of penetration is controlled by weld pool and its direction. As shown in below fig.12 at the location of weld pool due to high temperature there is tension and the part of the base material and last run weld metal which started to cools down have compression due to contraction (solidification of crystalline structure) of material after decrease in temperature.

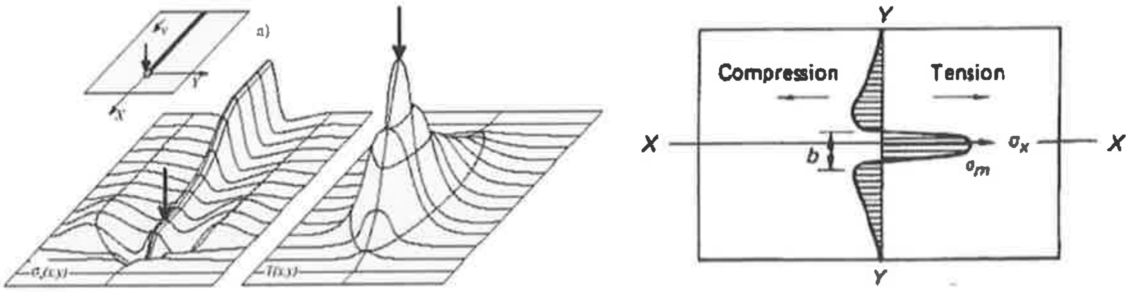


Figure 12 Temperature distribution along with length of weld joint [50]

2.3.2 THERMAL CYCLE IN HAZ AND EFFECTS OF PREHEAT/HEAT INPUT

As we know heat affected zone (HAZ) is small volume of base metal very near to fusion line whose structure totally changed due to intense heat of each weld bead. Temperature suddenly rises in HAZ and then decreases with cooling. This is not important that how fast it rises but it is very important how fast it goes down. Because this will decide the structure of HAZ. If it decreases very fast then brittle structure of martensite will form. In this situation preheat and heat input also plays an important role. When preheat applies then peak of that temperature increases and subsequently cools down whereas heat input magnifies the volume of each coordinate. This effect of preheat and heat input can be seen in below figure 13. (For Preheat temperatures refer to Annexure-2).

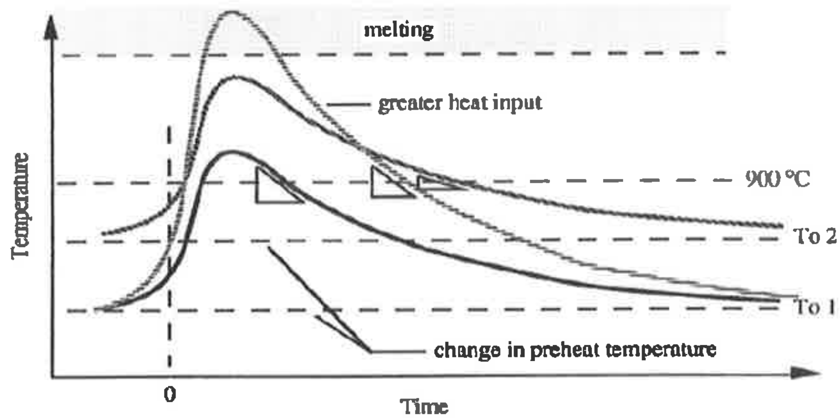


Figure 13 Effect of Preheat on thermal cycle of HAZ [50]

2.3.3 FLOW OF MOLTEN METAL AND FLUID FLOW IN WELDING

Fluid flow has important effect on deposition, penetration depth and HAZ therefore it also affect the mechanical properties and weld soundness/quality. There are three types of forces which act on molten metal [51]:

1- Gravitational force F_g, due to mass of the droplet

$$F_g = \frac{4}{3}\pi R^3 \rho_d \, g \tag{2.3}$$

2- Drag force F_d, is the force exerted on spherical body in flowing gas

$$F_d = C_d \frac{\rho v^2}{2} \pi R^2 \tag{2.4}$$

3- Lorenz force F_{em}, acts in planes perpendicular to current lines and become a detaching force.

$$F_{em} = \frac{\mu_0 I^2}{4\pi} \ln \frac{r_a}{R} \tag{2.5}$$

Fluid flow in weld pools faces the following forces [51]:

1- Buoyancy Force (BF): liquid metal density decreases with temperature increase and because of this at the center due to heat source liquid metal remains warmer as compare to liquid metal at edges. Therefore cooler heavier metal sinks down due to gravity and rises along the axis of pool.

$$\boldsymbol{BF = \rho \times V \times g} \tag{2.6}$$

2- Lorentz Force (F): is basically the driving force for fluid. Converging current field along with magnetic field causes downward and inward Lorentz force. Here liquid metal pushed down along pool axis and rises along pool boundary.

$$\vec{\boldsymbol{F}} = \boldsymbol{q\vec{v} \times \vec{B}} \tag{2.7}$$

3- Shear Stress sue to Surface Tension (Mα): Increase in temperature decrease surface tension. Therefore due to this warmer liquid having low surface tension is pulled outward by the cooler liquid having high surface tension.

$$\boldsymbol{Ma = -\frac{d\Upsilon}{dT}\frac{L\Delta T}{\alpha\mu}} \tag{2.8}$$

4- Marangoni Flow: if some surface acting agent presents then cooler liquid metal having lower surface tension is pulled inward by warmer liquid metal of high surface tension.

Sr .#	Region of Fluid Flow	Driving Force	Formula	Remarks	Mechanism
01	Weld Pools	Buoyancy Force	$BF = \rho \times V \times g$	BF=Buoyancy force ρ = Density g = Gravity	Refer to graphical representation as shown underneath
		Lorentz Force (Electromagnetic Force)	$\vec{F} = q\vec{v} \times \vec{B}$	$\vec{F}$ = force q = Charge $\vec{v}$ = Velocity $\vec{B}$ = Magnetic field	Refer to graphical representation as shown underneath
		Shear Stress due to surface tension gradient (at molten metal surface)	$Ma = -\frac{d\Upsilon}{dT}\frac{L\Delta T}{\alpha\mu}$	Ma = Marangoni number $\Upsilon = Surface\ Tension$ L= Characteristic Length α = thermal Diffusivity μ = Dynamic Viscosity $\Delta T = Temperature\ Gradient$	Marangoni Effect due to surface tension in absence of Surface Active agent as shown underneath
		Shear Stress induced due to Arc plasma on molten metal surface	$Ma = -\frac{d\Upsilon}{dT}\frac{L\Delta T}{\alpha\mu}$	Ma = Marangoni number $\Upsilon = Surface\ Tension$ L= Characteristic Length α = thermal Diffusivity μ = Dynamic Viscosity $\Delta T = Temperature\ Gradient$	Marangoni Effect due to surface tension in Presence of Surface Active agent as shown underneath

02	Fluid Flow in Arc (The forces which effect Droplets movement)	Gravitation Force (Due to mass of droplet)	$F_g = \frac{4}{3}\pi R^3 \rho_d\, g$	F_g = Gravitation force R = Droplet Radius ρ_d = Droplet Density	
		Drag Force (Due to flowing shielding gases)	$F_d = C_d \frac{\rho v^2}{2} \pi R^2$	F_d = Drag Force C_d = Drag Coefficient V = Flow Velocity	
		Electromagnetic Pinch Force (Due to Arc Pressure or detaching Forces or Lorenz Force)	$F_{em} = \frac{\mu_0 I^2}{4\pi} \ln \frac{r_a}{R}$	r_a = Radius of Arc μ_0 = Permeability of free space	

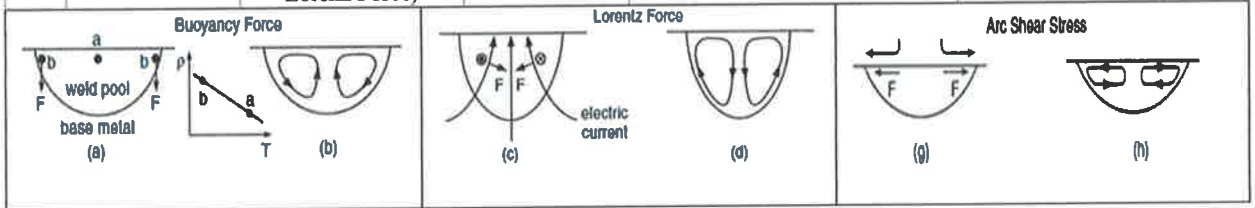


Figure 14 Forces involve in molten metal and fluid flow in welding

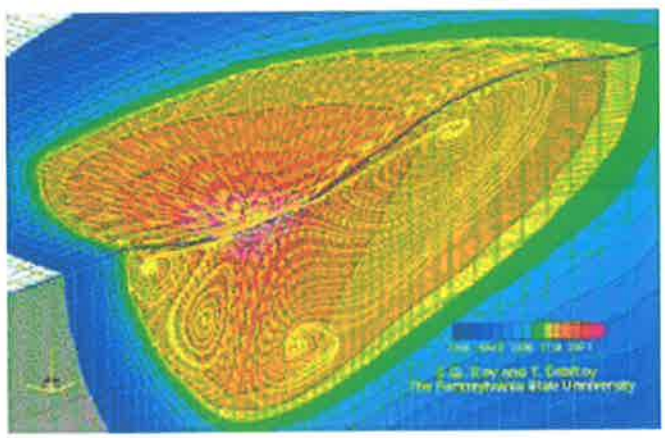


Figure 15 Fluid flow in weld pool [51]

2.3.4 POWER DENSITIES

Electric power per unit area is called power density and measured in Watt per square centimeters. Power density plays an important in creation of weld pool.

Power density and heat input values are inversely proportional to each other so it mean power density of heat source when increase then heat input value to work piece decrease. But any excessive heating can damage to workpiece and could cause distortion. By increasing the power density deeper penetration can be obtained with high weld speed and good weld quality. This is very important when stainless steel material is welded with

GTAW process. Normally arc welding processes have moderate power densities and heat input whereas high energy beam welding processes have high power densities and lower heat inputs. On the other hand gas welding processes have high heat input with low power densities.

Power density can be changed either by changing equipment rating or by changing spot size , changing the rating of welding equipment is expensive therefore spot size can be adjusted as required because decrease in spot size results a squared increase in heat intensities.

The width of heat affected zone (HAZ) is also related to power density. HAZ width is related to process interaction time and thermal diffusivity of solid and in case of low power densities , HAZ width change due to interaction time whereas in other of higher power density of welding process HAZ width is not depended on interaction time of heat source with work piece.

2.3.5 CARBON EQUIVALENT

Carbon plays important role in producing quality weld. Carbon equivalent has been derived whose intend is to consider the effect of all alloying element of parent metals and reflects their effects in terms of carbon and carbon equivalent is the sum of carbon content plus the effects of all other alloying elements. The purpose of all these efforts is to estimate the weldability, find Preheating / Post heat Treatment requirements and probability of getting Welds, Hardness & Hardenability of completed weld is directly and weldability of parent metal is inversely optional to Carbon Equivalent Number. American welding institute and derived below formula which is used to estimate hardness, hardenability and weldability of parent [52].

$$CE = \%C + \left(\frac{\%Mn+\%Si}{6}\right) + \left(\frac{\%Cr+\%Mo+\%V}{5}\right) + \left(\frac{\%Cu+\%Ni}{15}\right) \tag{2.9}$$

If carbon equivalent (CE) is less than 0.35 then weldability is excellent and is poor if CE is over 0.50.

Japanese welding engineering society used critical metal parameter instead of carbon equivalent and critical metal parameter is used to find susceptibility of parent metal weld cracking [52].

$$Pcm = \%C + \frac{\%Si}{30} + \frac{\%Mn+\%Cu+\%Cr}{20} + \frac{\%Ni}{60} + \frac{\%Mo}{15} + \frac{\%V}{10} + 5B \tag{2.10}$$

In carbon equivalent and critical metal parameter, only those elements other than carbon are considered that have direct influence on hardness, hardenability, weldability, toughness and strength.

2.3.6 HEAT INPUT

Heat input measures the amount of energy or heat supplied to parent metal to produce welded joints and can be calculated as follows:

$$\text{Heat Input (J/mm)} = \frac{\text{Voltage x Amperage x 60}}{\text{Travel Speed (mm/min)}} \tag{2.11}$$

For desired weld properties to produce balanced heat input to be used for weld joint. Normally thermal cycle of a weld is expressed by heat input-time-temperature cycle. It is also explained in para 2.3.4 that heat input is inversely proportional to power density.

Thermal efficiency of arc welding processes are also based on heat input. GTAW has the lowest thermal efficiency of 60-65% whereas SAW has the highest with 95-100% thermal efficiency.

Heat input has major effects not only on welding outputs but also on mechanical properties. Low heat input can problem arc initiation and excessive heat put can cause poor mechanical properties, distortion, cracks and burn through like welding defects.

2.3.7 FERRITE NUMBER

Ferrite number is the parameter which shows the total amount of delta ferrite in completed weld of austenitic steel. Ferrite number acceptable range is 5-20. Ferrite number plays important role in the quality of completed weld for austenitic steel. If ferrite number is lower than 5 then completed weld might undergo to hot cracking however austenitic steel weldment's protection against corrosion increased at lower ferritic number. Higher ferrite number might lead to brittle failure of weldments if welded austenitic joints exposed to higher temperature. To find ferrite number Schaeffler diagram, WRC 1992 and magnetic induction methods are normally used.

CHAPTER 3

WELD DEFECTS AND QUALITY ISSUES ASSOCIATED WITH WELDING

3.1 QUALITY OF WELDS

Quality of welds is defined as "the level of perfection that welds exhibits pertaining to the entire volume of weldment as well as to the profile of weld surface appearance". [53]

With reference of quality weld definition as defined above, the study has performed to find out the best welding condition. Productivity in term of quality is defined as "optimum blend of parameters which inevitably develop minimum or no defect then the process will result in high productivity."

3.2 WELD QUALITY ISSUES

Important parameters which can affect the quality of weld in SAW process are current which is related to feed speed, voltage which controls arc length beneath the flux layer. Electrode stick out affects amperage because power will be used to in resistance heating of wire and also travel speed because travel speed affects both on penetration as well as bead shape. Any abnormal combination can cause different defects in welds like porosity, lack of fusion, solid inclusion and shrinkage concavity [54]. On the other hand GTAW process can be used in controlled environment like in welding shops as well as in field where environment is difficult to control. This process is mostly used manually therefore operator factor and his capability is also related with this process. Due to these factors many weld and quality issues are associated with this process which are: tungsten inclusion, surface porosity, crater pipes and root oxidation. Therefore precautions need to be taken in order to get good weld quality.

Several problems [54] may occur when using the semiautomatic application method. Sometimes electrode ire when leaves the welding gun nozzle tends to curve and cause the arc to be struck which may not be expecting by operator. For deep narrow groove welds this curve cause arc to move more on one side as compare to other in the root which may cause incomplete root fusion. Sometime extra pass is required to maintain the exact weld size because weld is hidden under the flux but too much deposition is not required. Variation in root opening is also important because this affects travel speed. If travel sped is uniform then weld may be in under filled or over filled condition.

There is another quality issue of centerline crack which is mainly associated with extremely large single pass weld deposition. Because large impurities will move towards last freezing point which is centerline during solidification. If there is sufficient amount of these impurities then centerline cracks may occur. Single pass flat fillet welds are most appropriate case of this situation when base plates are at 45 degree angle. This can be avoid by varying the angle by 10 degree and by avoiding true 45 degree.

Hardness of deposited weld metal is another quality issue because hardness contribute to cracking during fabrication or during service. Too rapid cooling of carbon and low alloy steels or excessive alloys or inadequate PWHT are the main causes of this hardness. But in automatic machine welding defects may expected at start or end of the weld. So to avoid this run out tabs are used because in this case start and ends will come on these tabs.

Higher rate of deposition make SAW more valuable as compare to other arc processes. There are four factors which make higher deposition rate and are; 1- Polarity 2- long stick out length 3- flux additives 4- Additional electrode. Deposition rate will be higher for DCEN and for AC this is between DCEN and DCEP. This can also be increased by increasing the stick out length but this will reduce penetration. Metal additives in SAW fluxes also increase deposition rate and some additional electrodes can also be used to increase deposition rate.

Quality of deposited weld metal is also considered very high because here ductility exceeds the limit of mild steel and low alloy steel when correct combination of flux and electrode wire are used. This will also increase in fully automatic welding where human influence will be fully neglected so weld will more uniform and free from any discrepancies. Here higher bead size per pass can be obtained and more heat input and slow cooling rate make easier for gases to release. Moreover slag is also low in density so float out on the top. So we can say uniformity and consistency are the advantages when using automatic welding.

3.3 WELD IMPERFACTIONS

When variables are not properly controlled, welding conditions are not suitable and welding operator/welder skills are not up to the mark then weld may have different defects. These defects not only effect the weld quality of the weld but also make it suspicious for its intended use. Therefore controlling of variables and then identification and rectification/removal of those defects are very important. Due to different controlling variables and process applicability different defects are associated with different welding processes.

3.4 WELD DEFECTS IN SAW PROCESS

Following are the common defects which normally found in submerged arc welding process.

3.4.1 POROSITY

These are the gas filled cavities created during solidification of weld and expulsion or evaluation of gases from solution in solidifying weld metal. The term used to describe n areas of rounded gas pores is porosity. Porosity will be expected in deep SAW process due to damped welding fluxes or improperly cleaned plates. To prevent porosity, the surface to be welded should be clean and free of grease, oil, paints, moisture, and oxides.

Figure 16 Porosity on top surface of SAW weld [55]

3.4.2 SHRINKAGE CAVITIES

The internal voids or cavities which are formed during solidification of large and single weld of high depth/width ratio like weld profile. These may be defined as hot plastic tears and are due to high opposite contractional forces both in weld area or HAZ area until ductility is overcome resulting in a tear.

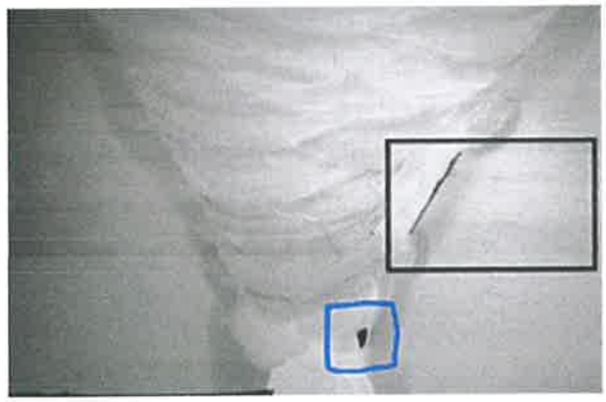


Figure 17 Shrinkage Cavity along with lack of fusion [56]

3.4.3 SOLID INCLUSION/SLAG INCLUSION

They can be metallic or non-metallic that are trapped in the weld and are really dependent on the welding process being used. In SAW which uses fluxes to form all required function of shielding and chemical cleaning, slag inclusion may occur. All slag from tack welds or previous layers should be removed.

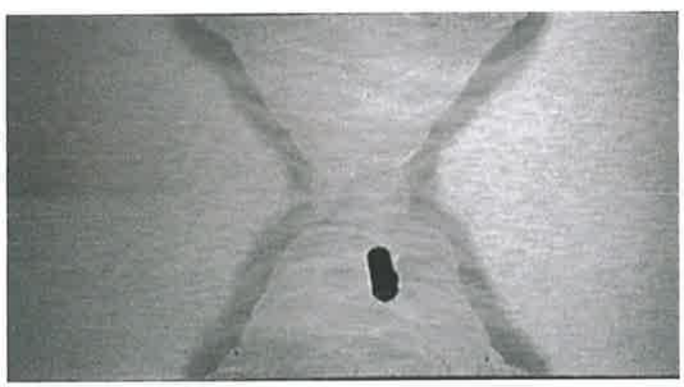


Figure 18 Solid/slag inclusion in double V groove weld [56]

3.4.4 LACK OF FUSION

Lack of fusion in SAW is mainly caused by Arc Blow (Lorenz Force) or some time poor tracking on double sided welds. Tack welds should be positioned so that the submerged arc weld completely melts out the tack.

Figure 19 Lack of side wall fusion [56]

3.4.5 CENTERLINE CRACKS

In SAW centerline cracks are mainly caused by high dilution & Sulphur pick up and can be minimized by proper selection of fluxes to be used.

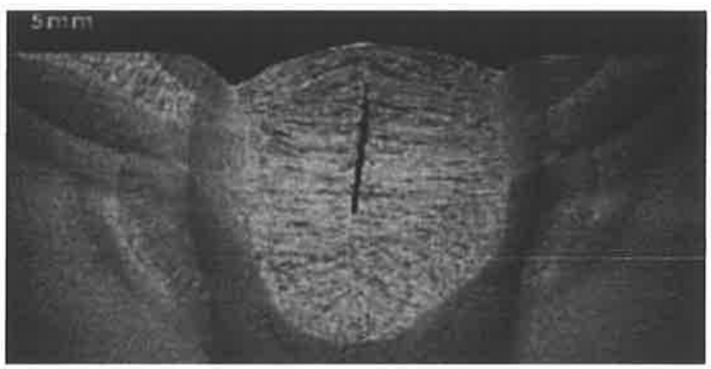


Figure 20 Center line crack in the middle of weld [56]

3.5 WELD DEFECTS IN GTAW PROCESS

Following are the common defects which are normally found in GTAW process.

3.5.1 TUNGSTEN INCLUSION

Tungsten inclusion is caused by a lack of welder skill, too high current setting which will melt the tip of electrode and/or vertex angle because incorrect vertex angle will also promote the tip to be broken while heating. This is metallic inclusion introduced in GTAW due to poor welding technique or too high amperage for the diameter of tungsten being used.

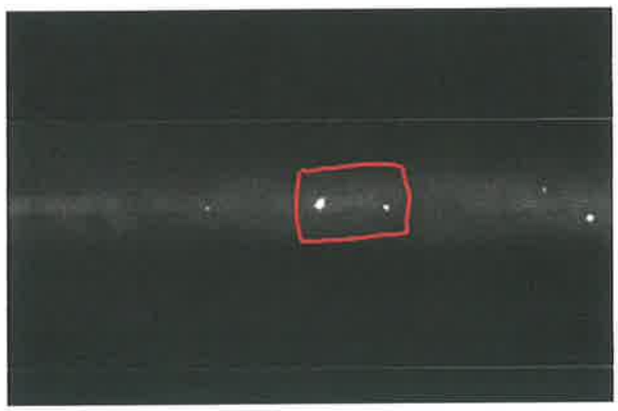


Figure 21 Radiography film showing Tungsten electrode inclusion [57]

3.5.2 SURFACE POROSITY

This is simply happen because of loss of shielding gas due to incorrect gas setting for joint or welding position or welding at site. A singular gas porosity cavity filled more than 1.5mm in dia. is called blowhole porosity. Blowhole porosity can occur in GTAW due to the same reasons mention above. But this can be diminish by proper cleaning of weld joint surface, correct setting of shielding gas flow and by avoiding damped consumables.

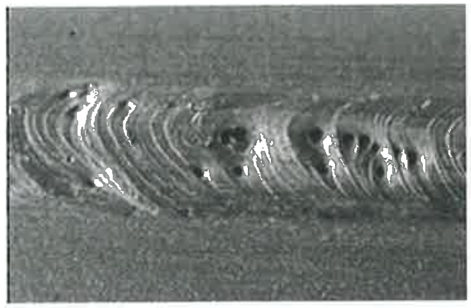


Figure 22 Porosities at the surface of weld [58]

3.5.3 CRATER PIPES

Poor finishing of weld joint or inadequate use of current decay can cause crater pipes. It normally happens at the end of weld due to insufficient filler metal to fill this crater.

Figure 23 Crater pipe at weld stop [59]

3.5.4 WELD OR ROOT OXIDATION

During welding of stainless steel or titanium alloys insufficient gas cut off delay or insufficient gas purging pressure can cause weld or root oxidation. This is simply due to welding of reactive metals like stainless steel with contaminated purging gas flow.

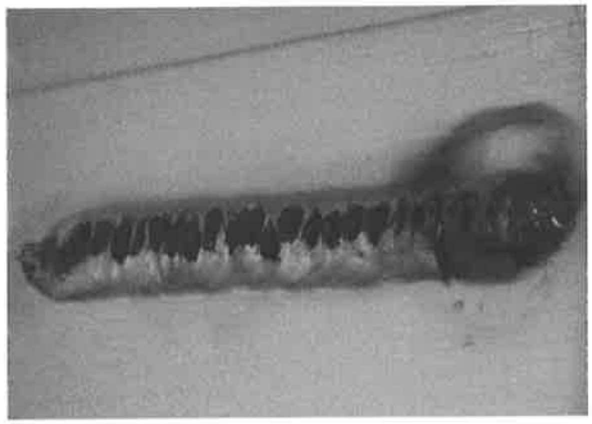


Figure 24 Root Oxidation [59]

3.6 ACCEPTANCE CRITERIA IN PRESENCE OF WELD DEFECTS

In fact in industries, where pressure welds is used to build facilities, reliability, quality and strength of completed weld is checked by intensive inspection and testing program. The results of the inspection program ensure that the produced welds are fit for service without any quality and safety hazard.

Quality monitoring program which includes "Inspection and Testing" is a way to get confidence that the produced welds is fit for service and will serve the purpose for intended service life. Different methods used for multipurpose evaluation of weld joints.

- Mechanical and Non-Destructive Testing
- Defects and Dis-continuities evaluation techniques
- Welds Test result evaluation Method

As mentioned above different methods are used to find these defects and then certain acceptance criteria as per applicable code and standard is followed to evaluate significance of defect in order to accept or reject that defect. Following are the references of few acceptance criteria's given in international code and standards which are followed in industry.

- ASME Sec VIII Div. I: Code for Pressure vessels and boilers, Clause UW51/52 & appendix-4
- ASME B 31.1: Code for power piping, clause 136.4.5
- ASME B 31.3: Code for Process plant piping, clause 341.3.2
- ASME Sec IX: Code for Welder and Welder qualification, Clause QW 191.2

CHAPTER 4

STANDARDS AND BEST FIELD PRACTICES

In Industry different international codes and standards are in use for constructions, fabrication, erection, qualification and inspection. As mentioned above these code and standards not only suggest for selection of base metal, filler metal, welding variables but also give a guide line to develop and accept welding procedures and welder/operator qualifications. Different NDT techniques are also utilized in accordance to these standards to evaluate tests for welding procedure/operators qualifications. Following are the few international code and standards which are commonly used in different fields of industry for procedure/operator qualifications:

- ASME BPVC Sec IX: Qualification standards for welding procedure and welding operator/welders
- API Std. 1104: Welding of pipelines and related facilities
- AWS D 1.1: Structural welding code – Steel
- API 577: API Storage Tanks

Here ASME BPVC Sec IX is generally followed for welding procedure/operator qualification. Here this standard is taken as reference to describe different parameters.

4.1 BASIC WELDING PARAMETERS

All the variable parameters which are considered during welding and variables which play an important role during qualification of any welding process and qualification of welder and welding operator are discussed here. Moreover, certain characteristics of these variables are also defined as essential, non-essential and supplementary essential variables in different standards.by considering their effect on mechanical properties and quality & soundness of weld.

Welding is always performed as per any welding procedure specification normally named as WPS. And in order to develop any WPS it is required to perform initial welding on test coupon and then performed destructive and nondestructive tests as per international standards to find the conformation of test results with desired results. This test coupon welding is called procedure qualification record and normally named as PQR. There are certain variables involve for qualification of PQR and development of any WPS where few are essential and few are non-essential and some are supplementary essential variables. Each welding process itself is an essential variable and has certain parameter related to its process which are also under the category of essential/non-essential and supplementary essential variables [60]. So in this chapter we shall discuss;

1- Welding Variables
2- Essential Variables (EV)
3- Supplementary Essential Variables (SEV)
4- Non-Essential Variables (NEV)
5- Procedure Qualification Record (PQR)
6- Welding procedure specification (WPS)

All these will be discussed in detail to find their importance and relevance with each other to perform a quality welding in any field of interest.

4.2 WELDING PROCEDURE /OPERATOR QUALIFICATION PARAMETERS

Following are the basic parameters which affect the qualification of any arc welding process. All international standards consider these parameters while defining their essential/Non-essential and supplementary essential variables [61].

- Type of base/parent metal
- Type of filler metal
- Welding positions and weld joint design
- Preheating and Post weld Heat Treatment
- Types of gases
- Techniques
- Electrical Characteristics

4.2.1 BASE METALS

A metal or metals which are going to join through welding is called bae metal. This may be of similar type or different types. Base metal plays an important role in welding and qualification of any welding process. There are different classification systems which divide different metals into different groups' base on their chemical composition, mechanical properties and product form. Following are the well renowned classification systems which are used all over the world.

- ASME Boiler and Pressure Vessel Code Material Specifications
- American society for testing & materials (ASTM)
- American Iron & Steel Institute (AISI)
- American Petroleum Institute (API)

In order to reduce the number of procedures base metals are divided into different P-numbers based on their properties and characteristics by ASME Boiler and Pressure Vessel Code Material Specifications. A following Table 1 will help to find which P numbers are assigned to which metal.

Table 1 P Numbers classification of Materials [61]

P Numbers	Base Metals	Sub-Detail
1 through 15F	Steel & steel alloys	P 1 - Mild carbon Steel
		P 3 - Low Alloy Steels
		P 4 - Chrome-moly Steels (1-1/4)
		P 5 - Chrome-moly Steels (2-1/4)
		P 8 - Stainless steel
21 through 26	Aluminium and Aluminium based alloys	
31 through 35	Copper and copper based alloys	
41 through 49	Nickle and Nickle based alloys	
51 through 53	Titanium and Titanium based alloys	
61 through 62	Zirconium and zirconium based alloys	

There are some materials and grades which are introduced by other international standard material organizations like ASTM, API or AISI which are acceptable to ASME but are not listed in their classification. So such materials are given **S numbers**. But now P numbers are reassigned to those metals which were previously assigned S numbers. AISI has categories materials as per following Table 2.

Table 2 AISI Material Classification [61]

AISI-SAE Classification			
10XX	Plain Carbon steel	43XX	Ni-Cr-Mo Steels
11XX	Re-Sulphurized grades	51XX	.8% Cr Steel
13XX	Manganese Steels	52XX	1.45% Cr Steels
40XX	Mo Steels	61XX	Cr-V Steels
41XX	Cr-Mo Steels	92XX	Si-Mn Steels
50B60	Boron Treated Steel		

Similarly API 5L Grade B/X40/X60/X70 [62] are different materials which are used in cross country pipelines. This base material is essential variable for qualifying any welding process and any change from the qualifying material range will require requalification of that material as per applicable code. Similarly any change in base material thickness from the range which is initially qualified will require requalification.

ASME Sec IX [61] also assigned Group numbers to base metals as subset of P numbers. G numbers come into play when WPS are required to qualify with impact testing which may be required by other sections or codes. These are based on comparable characteristics like base metal composition, its weldability and mechanical properties.

These classifications simply divide ferrous and non-ferrous metals into different groups' base on their chemical composition and mechanical properties. It shows different type of ferrous metals, their major alloying elements and important properties which make them useful in different areas of industry. Whereas famous non-ferrous metals include Copper & Copper alloys, Ni & Ni alloys. Aluminium & Aluminium Alloys, Titanium & Titanium Alloys etc. Ferrous metal classification is given in Annexure-1.

4.2.2 FILLER METALS

Any metal in the form of coated/flux cored electrodes, welding bare rod or wire which will melt and deposit to fill & form the weldment will be called filler metal. Type may be different depending upon type of welding process but purpose will remain same to provide deposit weld metal with desire properties and shielding for molten metal with coated electrodes and externally in case of bare rod or wire. Same like base metals electrodes and welding rods are also divided into different F numbers depending upon their usability characteristics. This will also help to reduce number of qualifications for huge numbers of materials and consumables. The grouping does not imply that base metals or filler metals within a group may be indiscriminately substituted for a metal that was used in the qualification test without consideration of the compatibility of the base and filler metals from the standpoint of metallurgical properties, post weld heat treatment design and service requirements, and mechanical properties. Therefore F numbers of filler metals are considered essential and any change from one F number to any other F number or any metal not listed here will require requalification. Following Table 3 will show ASME Sec IX [61] classifications for F numbers of different materials.

Table 3 F number classification of Filler Metals [61]

F Numbers	Electrodes/welding rods of Different Materials
1 through 6	Steel and steel Alloys
21 through 25	Aluminium and Aluminium based alloys
31 through 37	Copper and copper based alloys
41 through 46	Nickle and Nickle based alloys
51 through 56	Titanium and Titanium based alloys
61	Zirconium and zirconium based alloys
71 through 72	Hard facing weld Metal Overlays

Like F numbers "A" numbers are also assigned for ferrous metals based on weld metal chemical composition in ASME Sec IX [61]. Following Table 4 will show which "A" numbers are assigned to which materials.

Table 4 A number classification of Filler Metals [61]

A Number	Type of weld Deposit
1	Mild Steel
2	Carbon Moly
3	Chrome (up to 2%)-moly
4	Chrome (2% to 4%)-moly
5	Chrome (4% to 10.5%)-moly
6	Chrome - Martensitic
7	Chrome - Ferritic
8 and 9	Chrome - Nickel
10	Nickle up to 4%
11	Manganese-Moly
12	Nickle- Chrome - moly

Filler metal deposit thickness is also very important and affect the testing results if there is change in deposit thickness. Deposit filler metal thicknesses are given in respective applicable standards for qualification. Filler metal classification is also very important when there is notch toughness requirement so in that case any change in filler metal classification within or not cover in applicable specification or change in qualified trade designation of filler metal may alter the results.

4.2.3 PREHEAT

Preheating is used to reduce stresses in the weld and HAZ and to prevent any hard phase formation which causes loss of ductility and toughness of the material. This is also helpful to reduce chances of under bead cracking/HIC or delayed cracking. Sometime it is also used to dry the weld metal surface from moisture. Preheat is also applicable once welding is resumed after interruption. So preheat temperature and preheat cycle are two important tools which are normally considered. Therefore any change or decrease more than preheat temperature from the value originally qualified will need reconsideration.

Annexure -2 [63] shows preheat temperature values for different steel & alloy steel materials given in different ASME standards. Moreover any increase in maximum qualified PQR inter pass temperature may also affects impact test results. Basically inter pass temperature is temperature of weld area between each pass and always stated as maximum. Preheat and inter pass are always kept as per required values.

4.2.4 POST WELD HEAT TREATMENT

Post weld heat treatment is used to reduce residual, interlocking stresses in the material and to improve dimensional stability along with resistance to stress corrosion cracking (SCC). This is also helpful to reduce hardness in the material which may cause SCC or caustic embrittlement. PWHT depends upon composition and thickness of base metal and type of service for which it will use. And most important things are PWHT temperature, heating cooling rate and soaking time & temperature. PWHT can be performed by welding torch, electrical resistant heaters, and furnaces. Because of immense effect on material and weldment PWHT is also considered as an essential variable specially addition or deletion of PWHT, PWHT above or below transformation temperature or base metal thickness subject to PWHT. PWHT temperature for P numbers 1, 3, 4 & 5 are given below as per different international ASME standards [63].

PWHT temperature and time range become important in case of notch toughness requirements. Because these will affect the impact properties of material. So any change in these values will require requalification of procedure as per ASME Sec IX for any welding process.

4.2.5 TECHNIQUES

Technique is also an important parameter. If we see in ASME Sec IX where Use of thermal process is considered as an essential variable. When thermal processes are used to make weld groove for less than 16mm during fabrication and also employed for back gouging/grooving or removal for metals whereas initially not qualified then requalification is also required. Any change from multi pass to single pass per side will be considered when notch toughness requirements are there because this will cause change in weld volume and change in heat values.

4.2.6 GASSES

GTAW, Gas Metal Arc Welding (GMAW) and dual shielded Flux Cored Arc Welding (FCAW) welding processes use different type of shielded gasses. Normally helium, argon, CO_2 or their blend along with some addition of H_2 and/or O_2 are used. Type of gases affect the weldment and properties so few characteristics of gases are also classified as essential variables in some standards. And they ask for requalification in case of any change from one single shielding gas to other or to mixture of shielding gasses. Sometime deletion of shielding gas or change in nominal composition will also require requalification especially for root pass and may cause root defects during root & hot pass run of welding.

4.2.7 ELECTRICAL CHARACTERISTICS

Any increase in heat input and deposited weld metal volume over the qualified range will be considered when there is impact test requirements. In both cases there will be change in heat values absorb by the material so impact strength values can be changed. Heat in put can be calculated as given in section 2.3.6 equation 2.11.

And volume of weld metal can be measured by increase in bead size. In notch toughness requirement current polarity is also essential variable so any change from AC to DC or straight polarity to reverse polarity will also require to be considered because this will affect the heat input values.

4.2.8 WELDING POSITION AND JOINT DESIGN

Welding position is important because few process or mode of operation are dependable or give better quality of weld on specific welding position. For example SAW is performed in flat position, short circuit mode of GMAW in overhead position and Spray mode of GMAW in flat and vertical positions.

Weld joints design is also very important in terms of distortion. Both butt and fillet joints may experience distortion. However, distortion can be minimized by changing the type of joints like butt versus fillet single versus double side joint. This is because weld volume in joint affects local expansion and contraction. So more volume means more value of distortion. Therefore in this way weld joint design play a role. Normally five different type of joints are used which are Butt, Corner, Edge, Lap and Tee joints.

4.3 ESSENTIAL VARIABLES

A welding condition that will affect the mechanical properties of a weldment if that condition is changed. So it is important to note that any change in essential variable will require requalification of WPS [64].

4.4 SUPPLEMENTARY ESSENTIAL VARIABLES

A welding condition that will affect the impact strength of weldment due to heat input changes if the condition is changed. Impact strength is basically material's ability to absorb load energy rapidly applied to the part. Impact testing is carried out at specified temperature whereas code or type of base metal dictate minimum and average values of absorbed energy [64].

4.5 NON-ESSENTIAL VARIABLES

A welding condition that does not affect the mechanical properties of a weldment if the condition is changed. All type of non-essential variables define by any standard do not require requalification if need to be changed. But one thing is important that once non-essential variables are written on WPS need to change then WPS will be revised to depict those changes instead of doing the new changes on the same revision of existing WPS. In order to understand how variables are divided into EV, NEV & SEV let see how ASME Sec IX define these variables for GTAW, GMAW, FCAW and SAW processes. Now following figure will gave a comprehensive idea about this but their detail can be found in article II & IV of ASME Sec IX [61].

List of all variables defined in 4.3, 4.4 and 4.5 are given in Annexure – 3 [61].

4.6 PROCEDURE QUALIFICATION RECORD

Procedure qualification record normally named as PQR is a document which is occurred during welding of test coupon and testing results of that coupon. It should include at least all essential variables of that process which is proposed for that test coupon along with other required variables. Sometime PQR contains supplementary essential variables when impact test or notch toughness testing is also required for that job. As a successful acceptance of test results PQR is used to develop WPS but within the applicable ranges allowed by international code. PQR cannot be revised but any change in essential variables will require requalification of PQR. Sometime two or more PQRS can be used to develop one WPS or two or more WPSs can also be made from one PQR but within the ranges for which it initially qualified. Test results will remain part of PQR for future references.

The following steps are taken for performing PQR and then after to develop WPS accordingly [61][62][64].

- Drafting the preliminary WPS (PWPS) to perform test coupon welding and here preliminary variables (unapproved WPS) are selected according to parent material for which test coupon is going to be welded as per applicable qualification standard and previous experience.
- Weld test coupon is designed according to desire thickness and diameter and all actual parameters are noted during the welding
- Welding the test coupon as per PWPS at that welding position which will qualify the desire welding position
- After completion of welding testing of coupon is performed to find soundness of the weldment
- Then results are evaluated according to the acceptance criteria given in standards
- Documenting the test results

- After acceptance PQR is qualified and then WPS is developed based on that PQR in compliance with qualification code such ASME Sec IX, API 1104 AWS D1.1 etc.

As mention above PQR contains all essential variables and WPS include essential and nonessential variables. Now we shall discuss parameters which are taken into account during qualification and are classified as essential, non-essential and supplementary essential variables.

4.7 WELDING PROCEDURE SPECIFICATION

Welding procedure is a document which gives direction to welder or operator for making any weld. In other words purpose of qualifying welding procedure is to verify that the test weldment's mechanical and metallurgical properties are acceptable for the intended service of the weldment. WPS is responsibility of any manufacturer or contractor who is going to start welding so that specific WPS becomes his property. All WPS are made according to the international construction standards applicable to that scope of work. For normal plant/onshore/tanks/pressure vessels ASME Sec IX is followed for qualification of WPS, for cross country pipelines API 1104 whereas for carbon steel structure welding AWS D1.1 are used for qualification. Basically any WPS specify the conditions or ranges which shall be followed for welding. Therefore variables are divided into different categories depending upon their effect on the strength of welding joint and WPS enlisted those variables along with their ranges. Each WPS at least contain essential and non-essential variables and sometime supplementary essential variables if applicable. So simply we can say WPS determines that any specific weldment proposed for job is capable to provide required properties. WPS can be revised in case of any change in nonessential variables or due to any further supporting PQR but remember any change in essential variable of that WPS will require requalification of WPS. All WPSs give a range of welding variables which are essentially followed during welding. Therefore WPS helps to attain good weld quality by minimizing the chance of defects but welder/operator skills also play an important role to minimize imperfections.

4.8 NEED OF OPTIMIZATION IN SPITE OF STANDARDS TO ACHIEVE SUPERIOR QUALITY WELD

Since the standards are collaborative experience from customer voice which have large tolerances but within that window still there is a scope of improvement by rationalizing optimum tolerance settings. Hence in order to achieve this a comprehensive optimization will be required. Therefore design of experiment with desirability function are selected in order to perform optimization for SAW/GTAW processes and are discussed in next chapter.

CHAPTER 5

DESIGN OF EXPERIMENTS AND OPTIMIZATION

In this chapter following two methodologies are discussed to find the best weld conditions of GTAW and SAW processes in order to enhance the weld quality in the welding shop under similar welding environment;

- By Design of Experiment (DOE)
- By Desirability Analyses (DA)

5.1 DESIGN OF EXPERIMENT (DOE)

Conventional optimization processes normally utilize large no of experiments trials but on the other hand design of experiment is an economical way to conduct the experiments for the same purpose. Therefore this methodology has adopted for these analyses.

This method begins with defining the experiment objective and then selection of factors i-e process variables. Experiment design which gives layout for detailed experimental plan is the subsequent step and it increases the chances of information that will be obtained from no of experiments [65]. Following are DOE steps for conducting an experiment:

1- Defining the objective
2- Selection of process variables (factors)
3- Selection of experimental plan
4- Execution of design

5- Checking for the data

6- Verification of its consistency with assumptions made during experiment

7- Analyzing the results

8- Presentation of the results

The main objective of this thesis is to develop design of experiments for GTAW and SAW welding processes in order to find optimized weld conditions for best weld quality in the welding shop by considering both productivity and quality together. For this optimization process all steps as described in section 1.4 are followed.

5.2 OPTIMIZATION OF GTAW PROCESS VARIABLES

Gas tungsten arc welding (GTAW) is widely used for many welding application in the fields of fabrication, manufacturing and construction. As we know quality of weld is the level of perfection that welds exhibits pertaining to the entire volume of weldment as well as weld surface appearance and there are several controllable process parameters which may affect the quality of weld in terms of desire weld mechanical/chemical properties, shape, bead and free of imperfections. Codes and standards provide a range for weld process parameters but author experienced that still there is a window to further optimize these parameters to produce the quality weld. Therefore in this present work it was focus to improve the process by optimizing key parameters using design of experiment based advanced statistical tools. S/N ratio analyses are performed to investigate the selected variables optimal values along with ranking of factors based on significance and central composite design (CCD) and desirability analyses were used for optimization and simulation application to get the optimum variables values in order to enhance the quality of welds in terms of improving ultimate tensile strength, hardness and defect free weldments of Stainless steel material.

5.2.1 DESIGN METHODOLOGY

In this study orthogonal array method of Taguchi technique [66] with three levels of three welding variables (Current, gas flow rate and travel speed) and two responses (Ultimate tensile strength and hardness) were selected. Then S/N ratio for each process level was computed for analyses where highest level of S/N ration was corresponded to optimal level of process parameters. Then S/N ratio for "largest the best" target was calculated for UTS and "smaller the better" for hardness. By design of experiment using central composite design (CCD) of regression analyses used for optimization [67] along with desirability function [68]. ANOVA for variance analyses [69] was also performed. Finally confirmation weld was welded to ascertain the optimization results.

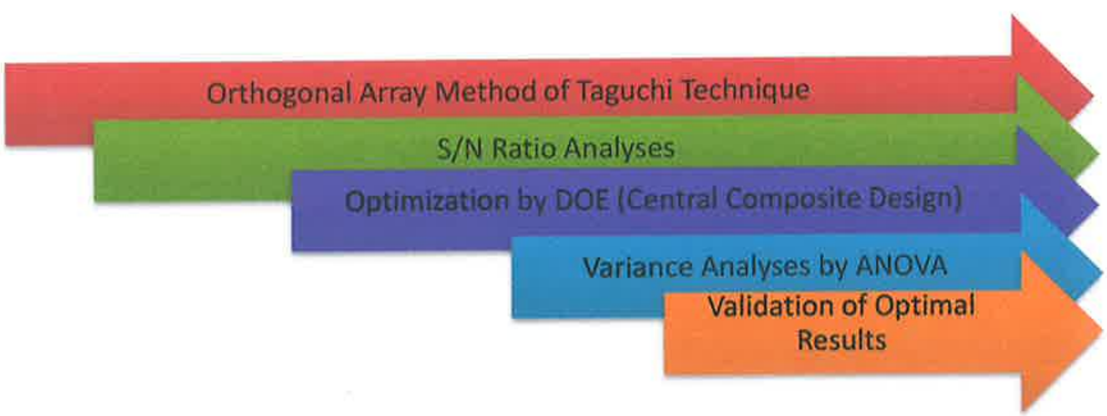


Figure 25 Design methodology for GTAW optimization

5.2.2 EXPERIMENT SET UP AND PLAN

In the shop ASTM A240 TP 304L of 6mm thickness stainless steel plate material is used for each run of welding with single bevel angle. This material was selected because this is common stainless steel material which is used for fabrication and manufacturing of pressure vessels, heat exchangers, and tanks in oil and gas field. Chemical composition of this material is given below [70]:

Specification	Type	Carob, C	Manganese, Mn	Phosphrous, P	Sulfur, S	Silicon, Si	Chromium, Cr	Nickel, Ni	Nitrogen, N
A 240	Austenitic (Chromium-Nickel) (Chromium-Manganese-Nickel)								
	304L	0.03	2	0.045	0.03	0.75	17.5-19.5	8.0-12.0	0.1

Where response values for each run are measured and taken from actual testing performed in Mechanical test Lab. Specimens for tensile testing were prepared from weld pieces in transverse direction to the welds in transverse and tensile testing was performed by using GALDABINI SUN60-V630 machine (where UTS=Max. Load/Original cross section area). Then hardness of weld and HAZ area were measured by using Wilson Hardness 432SVD machine. Average of hardness readings for each piece was used to present hardness value for weld metal. Weld Joint design, geometry and typical layout for hardness testing locations are given below in Fig. 26 and GTAW welding equipment, UTS and Hardness machines used for this experimental work are shown in Fig 27.

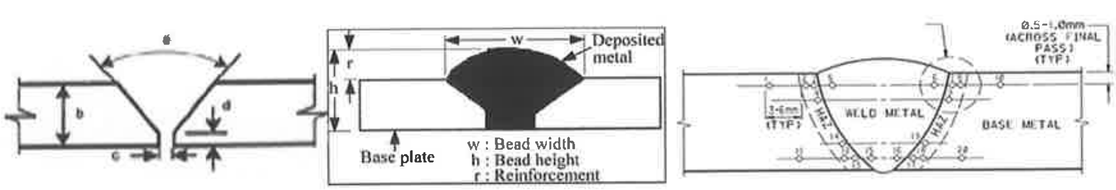


Figure 26 Weld Joint Design/geometry and hardness test location [WPS used for welding given in Annexure-4]

Figure 27 GTAW Welding Equipment, UTS and Hardness Machines used for Experiment Work

Experimental layout of this study was consist of L9 orthogonal array. Three important variables (A: Current, B: Gas flow Rate and C: Travel speed) were selected with three levels of each factor and two responses (Y1: UTS, Y2: hardness) as shown in Tables 5 & 6. Factors are continuous where continuous means those factors which can be assigned some numerical values. Reference WPS is given in Annexure 4. Level of process variables and relevant response values are shown in Table 7. S/N ratio for each level of process variable was computed for analyses where higher value of SN ratio related to better quality characteristics. Therefore optimal value was that having highest S/N ratio. S/N ratio for each response like UTS and hardness and ranking of variables based on difference was calculated and is given in Table 8 and Table 9. Formulas largest the best and smallest the best used for these calculations are given in below equations where n is number of variables and Y is value of responses.

$$S/N \text{ (Larger the better)} = -10 * \log \left(\sum (1/Y^2)/n\right) \tag{5.1}$$

$$S/N \text{ (Smaller the better)} = -10 * \log \left(\sum (Y^2)/n\right) \tag{5.2}$$

Table 5 Factors for experiment

Name	Units	Type	Role	Level 1	Level 2	Level 3
A:Current	Amp	Continuous	Controllable	80	115	150
B:Gas Flow rate	L/Min	Continuous	Controllable	8	10	12
C:Travel Speed	mm/Min	Continuous	Controllable	80	95	110

Table 6 Responses Selected for experiment

Name	Units	Analyze	Goal
Y1: Ultimate Tensile Strength (UTS)	MPA	Mean	Maximize
Y2: Hardness	HRB	Mean	Minimize

Table 7 GTAW L9 orthogonal arrays data for experiment

Experiment No.	Levels			Factors: Current (A) (Amp)	Factors: Gas Flow Rate (B) (L/Min)	Factors: Travel Speed (C)) (mm/Min)	Responses: UTS (Y1) (MPa)	Responses: Hardness (Y2) (HRB)
1	1	1	1	80	8	80	496	87.96
2	1	2	2	80	10	95	507	84.68
3	1	3	3	80	12	110	555	91.42
4	2	1	2	115	8	95	526	85.26
5	2	2	3	115	10	110	544	77.39
6	2	3	1	115	12	80	511	79.88
7	3	1	3	150	8	110	571	81.44
8	3	2	1	150	10	80	533	75.11
9	3	3	2	150	12	95	564	72.66

5.2.3 S/N RATIO ANALYSES

From Table 8 and Table 9 we can see S/N ratio of factors and effect on responses from ranking of each factor. For hardness we can see from factors rank (a) gas flow rate has major effect along with travelling speed whereas current has least impact. Because low gas flow rate cause porosity and very high gas flow rate cause to increase brittleness. Then very high/low travelling speed cause sudden increase and decrease in the temperature of weld joint and HAZ which results high hardness which is not desirable. Similarly from Rank (b) we can see current and gas flow rate have major impact whereas travel speed has the least. This is because current along with proper gas flow rate affect weld quality by controlling metal transfer, penetration, spatter control, post weld cleaning and by influencing metallurgical and mechanical properties. From these analyses a high value of UTS i-e 564 MPa was observed when current was 150 A and gas flow rate value 12L/min. Similarly lower value of hardness 72.66 found when Gas Flow rate was 12l/min with travel speed of 95 mm/min.

Table 8 S/N Ratio for responses SN-L for UTS and SN-S for hardness

UTS Y1	Hardness Y2	Y1^2	y2^2	SN-S	1/y1`2	1/y2`2	sum	SN-L
496	87.96	246016	7736.962	-51.0338112	4.0648E-06	0.00012925	0.00013331	19.3756134
507	84.68	257049	7170.702	-51.209352	3.8903E-06	0.00013946	0.00014335	19.2180621
555	91.42	308025	8357.616	-51.9918262	3.2465E-06	0.00011965	0.0001229	19.5522789
526	85.26	276676	7269.268	-51.5220464	3.6143E-06	0.00013757	0.00014118	19.2511376
544	77.39	295936	5989.212	-51.7886938	3.3791E-06	0.00016697	0.00017035	18.8433406
511	79.88	261121	5279.476	-51.2670512	3.8296E-06	0.00018941	0.0001546	19.0539111
563	81.44	316969	6632.474	-52.0716088	3.1549E-06	0.00015077	0.00019257	18.5770835
533	75.11	284089	5641.512	-51.6096424	3.52E-06	0.00017726	0.00018078	18.7142785
571	72.66	326041	6380.814	-52.2065952	3.0671E-06	0.00015672	0.00015979	18.9822941

Table 9 S/N Ratio and ranking for factors

Factors	Current, A	Gas Flow Rate, B	Travel Speed, C	Factors	Current, A	Gas Flow Rate, B	Travel Speed, C
low	-51.4117	-51.5875	-51.3035	**low**	19.38198	19.20301	19.04793
High	-51.7443	-51.6564	-51.7984	**high**	18.90367	18.99316	19.0707
Delta (Difference)	0.33261	0.068878	0.494852	**Delta**	0.478311	0.209856	0.022765
Rank (a)	1	3	2	**Rank (b)**	**3**	**2**	**1**

5.2.4 DESIGN OF EXPERIMENT BY CENTRAL COMPOSITE DESIGN

For this study Central Composite Design (CCD) [74] which is response surface methodology is used for designing an experiment because it fits quadratic model with sequential experiments and is very useful and accurate model for confounded factor interactions and quadratic effects up to 4th order [75].

Quantitative relation between responses and factors in term of response surface methodology can be expressed as follow:

$$Y = f\,(\text{Current, Gas flow rate, Travel speed})$$

Whereas Y is the responses which are to be optimized and other is function of the controllable factors. The system behavior will be obtained through quadric model which is developed by the least square method by considering the interaction of factors to maximize or minimize the response variables and below is Equation derived by Douglas C. Montgomery in statistical quality control and can be used for the development of quadratic model.

$Y = \beta_0 + \beta_1$ (Current) + β_2 (Gas flow rate) + β_3 (travel speed) + β_{11} (Current^2) + β_{22} (gas flow rate^2) + β_{33} (travel speed^2) + β_{12} (current*gas flow rate) + β_{13} (current*travel speed) + β_{23} (gas flow rate*travel speed) (5.3)

Here betas are coefficients of linear, quadratic and interaction of input factors. The β_0 is the intercept term whereas β_1, β_2, β_3 and β_{11}, β_{22}, β_{33} are the linear terms and interaction between variables terms respectively. In order to give flexibility in design additional levels can also be defined by introducing star/axial and center points.

Formula for calculating no of experiments is, $N = 2^n + 2*n + n_c$

Here N is total no of experiments, n is no of factors and n_c is no of star points as shown in fig 28.

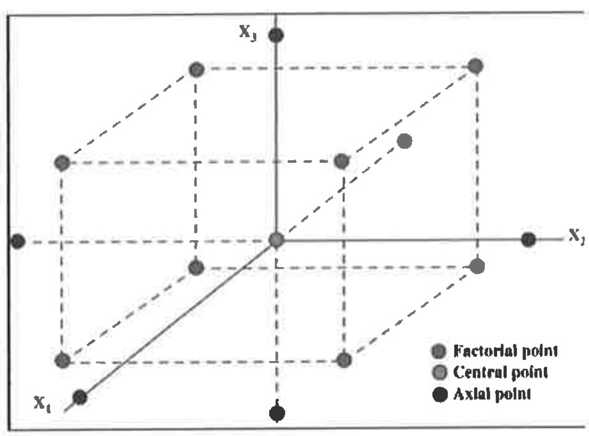


Figure 28 Selection of factors level in Central composite design (CCD)

The design is rotatable in composite design because it provides constant prediction at all points that are equidistant from the design center which is placed in last. The star points in rotatable center composite design are the distance of each axial point. With three factors and n_c =4 star points 18 experiment runs are calculated by using above formula and with one replica total 36 experiment runs are obtained. The DOE is summarized in Table 10 and detail of experiment data is given in Table 11 [77].

Table 10 Design of Experiment

Type of Factors	Design Type	CenterPoint Per Block	CenterPoint Placement	Replica	Design is Randomized	Total Runs
Process	Central composite design: 2^3 + star	12	Last	yes	Yes	36

Table 11 Experiment data of CCD Analyses

Run	A- Current	B-Gas Flow Rate	C-Travel Speed	Y1- UTS	Y2- Hardness	Desirability
Unit	(Amp)	(L/Min)	(mm/Min)	(MPa)	(HRB)	d1/d2
1	150	12	80	562	75.25	0.904/0.846
2	80	8	110	496	84.68	0/0.352
3	80	12	110	555	74.92	0.808/0.863
4	150	10	110	548	75.26	0.712/0.846
5	80	12	80	516	73.53	0.273/0.936
6	150	12	110	543	72.32	0.643/1
7	80	8	80	496	87.03	0/0.229
8	150	8	110	533	78.91	0.506/0.654
9	80	8	95	529	77.66	0.452/0.720
10	115	8	80	510	79.96	0.191/6
11	115	8	95	519	75.87	0.315/0.814
12	150	10	80	534	76.03	0.520/0.805
13	150	12	95	563	72.66	0.917/0.982
14	115	8	110	522	81.49	0.356/0.519
15	80	8	80	504	85.96	0.109/0.285
16	80	10	95	507	84.68	0.150/0.352
17	150	8	95	506	78.69	0.136/0.667

18	150	8	80	511	79.48	0.205/0.625
19	115	10	110	531	76.23	0.479/0.795
20	115	12	80	511	78.51	0.205/0.676
21	80	10	80	519	77.66	0.315/0.720
22	80	10	95	516	76.41	0.273/0.786
23	150	12	95	565	72.46	0.945/0.992
24	115	12	95	556	74.61	0.821/0.880
25	115	12	110	534	73.09	0.520/0.959
26	150	10	80	543	75.11	0.643/0.854
27	150	10	95	535	78.76	0.534/0.662
28	80	10	110	513	77.89	0.233/0.708
29	80	12	95	527	73.68	0.424/0.928
30	115	10	80	523	75.21	0.369/0.848
31	115	10	95	544	77.54	0.657/0.726
32	80	12	110	555	91.42	0.808/0
33	115	8	95	526	85.26	0.410/0.322
34	115	10	110	544	77.39	0.658/0.734
35	115	12	80	513	78.58	0.233/0.672
36	150	8	110	569	80.15	1/0.590

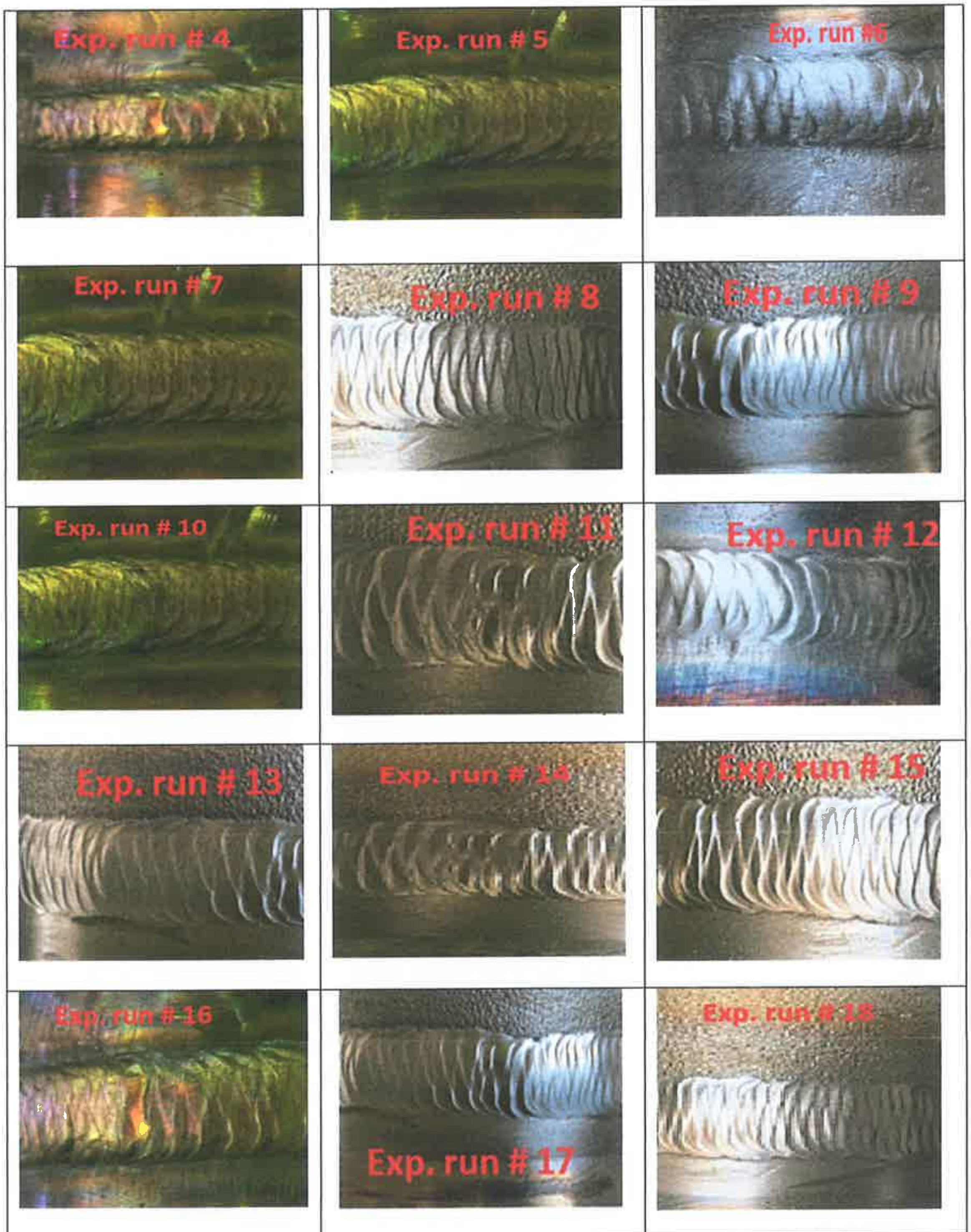


Figure 29 Typical images of some weld seams based on experiment runs [Image Magnification 2X]

5.2.5 VARIANCE ANALYSES BY ANOVA

The variance's analysis is performed by ANOVA and is conducted to investigate the controllable factor's influences on measured responses by P-value by using Stat Graphics software [72]. In Hypothesis testing P-Value is probability for a given statistical model, when null hypothesis is true, to determine significance of results. Hypothesis testing is hypothesis that is tested on the basis of observing a process that is modeled via set of variables and used to test the validity of a claim that is made about a population. Null Hypothesis is a default position that there is no relationship between two measured parameters. Before performing experiment, first choose a model and threshold value of p which is called "significance level", normally 5% or 1% and denoted as α (here 5% has selected). Normally 5% or 1% and denoted as α (here 5% has selected). A small p-value (typically ≤ 0.05) indicates strong evidence against the null hypothesis, so you reject the null hypothesis. A large p-value (> 0.05) indicates weak evidence against the null hypothesis, so you fail to reject the null hypothesis. P values very close to the cutoff (0.05) are considered to be marginal (could go either way). Degree of freedom tells about independent no of informations that went into calculation of estimate & depends upon exact design of your test. If Df is 1 then it all about mean.

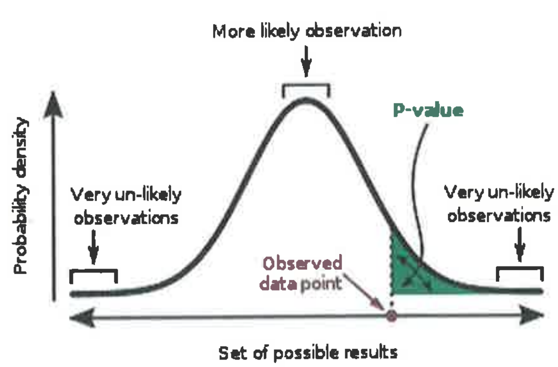


Figure 30 Significance of p-value

The F ratio is the ratio of two variances when the null hypothesis is true. Variance measure of dispersion and is square of standard deviation. You expect F to have a value close to 1.0 most of the time. A large F ratio means that the variation among group means is more than you'd expect to see by chance and vice versa. R-squared is called coefficient of determination [71] and it statistical measure of how data is close to regression line. It is between 0-100% where 0 shows no variability of response data around its mean and 100 means all variability around its mean. Value of this will show percentage response variable variation and higher value of this obviously mean data is well fitted in the model.

The analyses of variance are calculated for each response in the manner as calculations are made for S/N ratio analyses in section 5.2.3 and here only final results are explained below in Table 12 for weld hardness and Table 13 for ultimate tensile strength and standard Pareto charts are drawn as shown in Fig. 31. The statistical significance can be obtained by comparing mean square with estimated experimental error. If calculated P-Value [where P-Value= F.DIST (F ratio, Df1, Df2, False)] is less than 0.05 (α=5%) then those factors and their interaction are significant in these analyses whereas Value of R-Squared is calculated to explain the fitted in term of variability in the model.

Table 12 Variance Analyses for hardness

Hardness	Sum of Squares	Df	Mean Square=Sum of Square/Df	F-Ratio=Mean Square/Error	P-Value
A:Current	55.6206	1	55.6206	2.10	0.4984
B:Gas Flow rate	13.9458	1	13.9458	0.53	0.0401
C:Travel Speed	89.5540	1	89.5540	3.38	0.0487
AB	42.0986	1	42.0986	1.59	0.2480
AC	70.1808	1	70.1808	2.65	0.1478
BC	4.04630	1	4.04630	0.15	0.7077

R-sq. = 77.9316 %, R-sq. (adjusted for d.f.) = 46.4052 %, Std. Error of Est. = 5.14914, Mean absolute error = 2.75586

ANOVA Table 12 [72] shows variability in hardness values by considering each factor separately as well as their interactions. If P-Value is less than 0.05 then then those factors and their interaction are significant in these analyses. All P values less than 0.05 are highlighted in red in Table 12. Therefore based on P values from this table we can say gas flow rate and travelling speed have direct significant effect on hardness. Although P values for interaction of travel speed and current (AC) is more than 0.05 but difference is very less. R-squared value shows model is fitted 77.93% of variability in hardness. Similarly standard error, which quantifies the precision associated with statistical analyses, is 5.15. Mean absolute error which is average of absolute errors and it quantifies how close the forecast or predictions are. Less value mean less error which is in this case is 2.76. This is also obvious from below standardized Pareto chart which is drawn for hardness in Fig. 31.

Table 13 Variance analyses for UTS

UTS	Sum of Squares	Df	Mean Square=Sum of Square/Df	F-Ratio=Mean Square/Error	P-Value
A:Current	8779.18	1	8779.18	81.81	0.0375
B: Gas Flow Rate	3265.09	1	3265.09	30.43	0.0419
C:Travel Speed	666.002	1	666.002	6.210	0.0833
AB	61.8857	1	61.8857	0.580	0.0472
AC	4.72500	1	4.72500	0.040	0.2398
BC	1138.67	1	1138.67	10.61	0.6539

R-sq. = 96.4706 %, Std. Error of Est. = 10.3591, Mean absolute error = 5.20509

ANOVA Table 13 [72] shows variability in ultimate tensile strength values by considering each factor separately as well as their interactions. All P values less than 0.05 can be seen in Table 13. From this table we can say current has significant effect on tensile strength along with combination (AB) with gas flow rate. This is because current also governs arc initiation and its instability and high change in current can also affect weld strength and weld quality by metallurgical effects as well. R-squared value (as explained in hardness analyses under Table 12) shows model is fitted 96.4706% of variability in tensile strength. Similarly standard error is 10.3591 and mean absolute error is 5.20509.

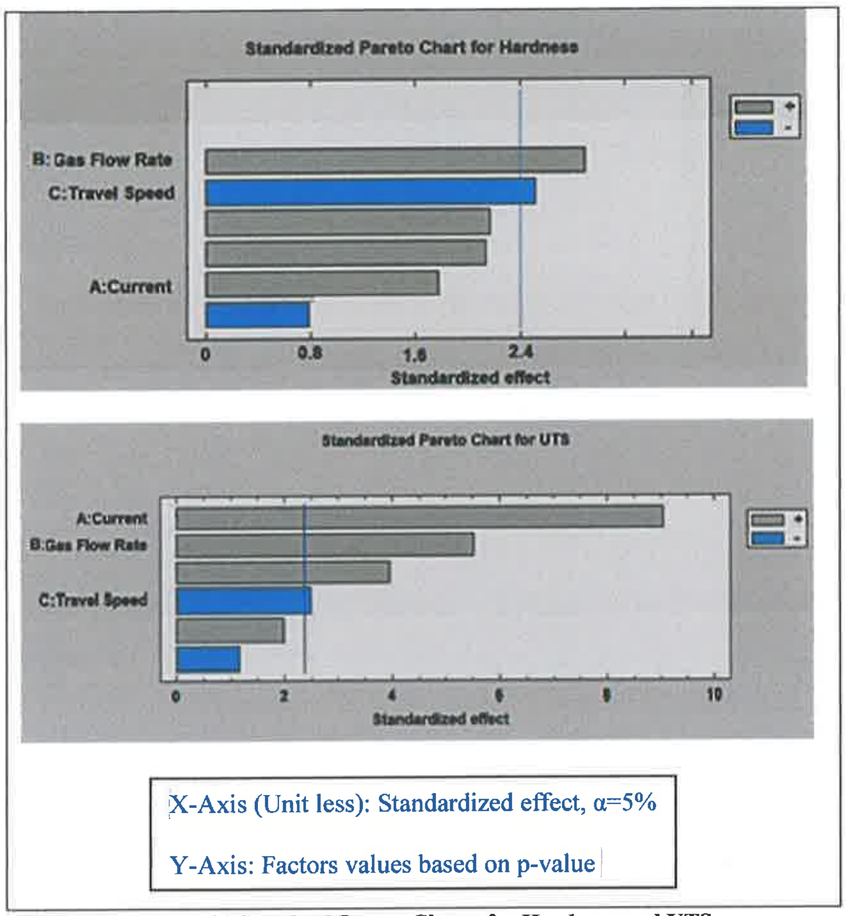


Figure 31 Standard Pareto Charts for Hardness and UTS

Based on above variance analyses standard Pareto charts are drawn for hardness and UTS [72]. The Pareto chart shows the absolute values of the standardized effects from the largest effect to the smallest effect. Reference line, depends upon significant level and indicates which effects are statistically significant. X-Axis showing standardized effect of affecting factors and is unit less whose cut off p value has selected 2.5 (α=5%) on scale and bars are drawn for major affecting factors and their combinations along Y-Axis. Two colors with sign +/- shows factor's increasing/decreasing effects. From hardness chart we can see gas flow rate has major effect along with travel speed and similarly for UTS current and Gas flow rate have major effect.

5.2.6 DESIRABILITY FUNCTION

The desirability function and loss functions are two methods which are normally used for optimization. But desirability function has more applicability and flexibility as compared to loss function. According to Herrington the conversion of every response value into scale free value is known as desirability [73] and can be calculated as per equation 5.4 developed by Herrington. And he was the one who developed this approach for optimization of multiple responses by,

$$D_i = \exp\left[-\exp\{-x_i\}\right],\ 0 \leq D_i \geq 1 \qquad (5.4)$$

Where Di is desirability, x is response for i indexes.

Later this was extended by Derringer and Suich by considering nominal the best (NTB), larger the best (LTB) and smaller the best (STB). Basically desirability function approach is very useful for multi response processes optimization. Here idea is that quality of process having multiple characteristics with any one of them is outside the desired limit is unacceptable. Actually this method finds that operating conditions which provide desirable response values.

Depending upon whether a particular response will be maximized, minimized or assigned a target value different desirability functions can be used. In our study we have selected larger the best (LTB) for UTS and smaller the best (STB) for hardness desirability response and can be calculated as given in below Equations Here d_i is desirability function, y_i is the response, USL_i is upper 95% limit and LSL_i is the lower 95% limit. Desirability ranges from zero to one and highest value will be the optimal. Generally 0.7 and above is considered satisfactory.

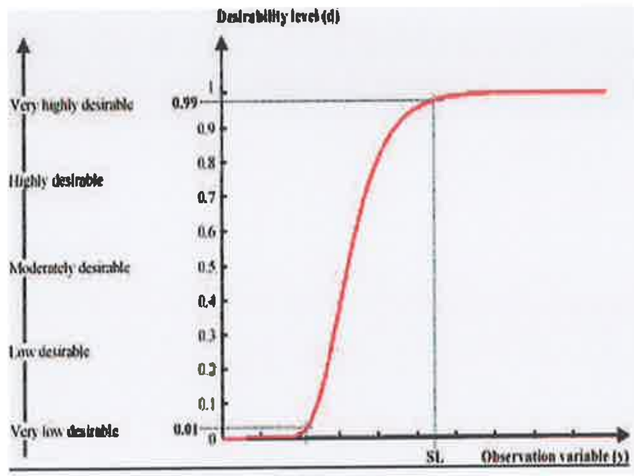


Figure 32 Desirability function levels

Individual desirability for each response can be obtained as given in equation 5.5 and 5.6 developed by Derringer and Suich for larger the best and smaller the best.

$$d_i = \begin{cases} 0, & \hat{y} \leq Y_{min} \\ \left(\frac{\hat{y}-Y_{min}}{Y_{max}-Y_{min}}\right), & Y_{min} \leq \hat{Y} \leq Y_{max}, r \geq 0 \\ 1, & \hat{y} \geq Y_{min} \end{cases} \quad (5.5)$$

$$d_i = \begin{cases} 1, & \hat{y} \leq Y_{min} \\ \left(\frac{\hat{y}-Y_{max}}{Y_{min}-Y_{max}}\right), & Y_{min} \leq \hat{Y} \leq Y_{max}, r \geq 0 \\ 0, & \hat{y} \geq Y_{min} \end{cases} \quad (5.6)$$

By using these equations individual desirability of each response was calculated for each run and are given in Table 11. Individual desirabilities are then combined using the geometric mean, which gives the overall desirability D as per below equation 5.7:

$$D = \{d_1(Y_1)d_2(Y_2)..........d_k(Y_k)\}^{1/k} \quad (5.7)$$

After performing this optimal values, obtained using above equation 5.7 for responses, are given in below Table 14 here D is overall desirability of each response and D* is overall process desirability and is geometric means of both overall desirabilities D.

Table 14 Optimal values for responses

Response	Optimized	Optimal	95.0% Limit	Desirability (D)
UTS (MPa)	yes	562.891	570.276	0.813
Weld Hardness (HRB)	yes	70.435	79.90	0.845

Overall desirability, D*= 0.82

Optimized settings of factors are obtained based on optimized desirability vs optimized responses values and are given in Table 15 and graphical representation is shown in Fig. 33.

Table 15 Factors setting at optimum

Factor	Setting
Current (Amp)	145
Travel Speed (mm/Min)	90
Gas Flow Rate (L/Min)	12

From S/N analyses in section 5.2.3 it was observed that desired values of UTS and hardness were 564MPa and 72.66 when factors values were for Current 150 amp, gas flow rate 12 L/Min and travel speed 95mm/Min. By using desirability analyses the optimal values obtained for responses are 562.891 MPa and 70.66 whereas optimal values of factors are for Current 145 amp, gas flow rate 12 and travel speed 90.2 mm/Min. Both results are much closed to each other.

On the other hand after S/N analyses factors were ranked based on their effect on responses. The same rank of factors found in ANOVA analyses where factors were ordered based on p-values.

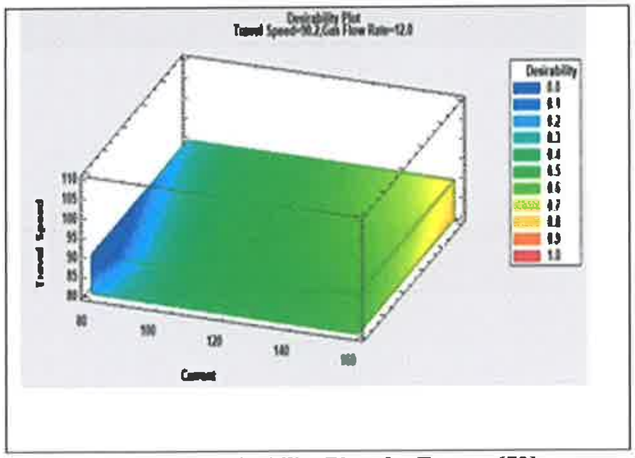


Figure 33 Desirability Plots for Factors [72]

The graphical presentation of desirability plots for factors is shown above in fig. 33 showing optimal values of current, gas flow rate and travel speed as mentioned in Table 15. Desirability (D) for both responses and overall process (D*) found about 0.8 as mentioned in Table 14 and are therefore shown as yellow/orange area in the top right portion as per color contrast range given in the above figure.

5.3 OPTIMIZATION OF SAW PROCESS VARIABLES

Joining of metals is very useful concept which is being utilized since Bronze Age and then gradual advancement gave rise to development of modern welding. And now welding is increasingly used in the fields of fabrication, manufacturing and construction. But productivity is the main concern in many manufacturing and industrial welding applications. Therefore selection of a welding process and its variables/parameters without sacrificing weld quality with respect to productivity and its quality is very important because an optimum blend of parameters which inevitably develop minimum or no defect will result in high productivity. For this study SAW process is also selected because this versatile welding process is the first choice whenever good productivity with high quality requires. Weld quality is the level of perfection that welds exhibit pertaining to the entire volume of weldment as well as to the profile of weld surface appearance. There are many variables which affect SAW process. But here we have focused on four important controllable factors of current, voltage, travel speed, and heat input to study theirs's effects on ultimate tensile strength (UTS), weld hardness, deposition rate, bead width and reinforcement in order to find best weld by using orthogonal factorial method (OFM) and desirability analyses.

5.3.1 DESIGN OF EXPERIMENT METHODOLOGY

In this study orthogonal factorial method (OFM) is used for modeling the responses and desirability analyses (DA) are used for optimization [73].

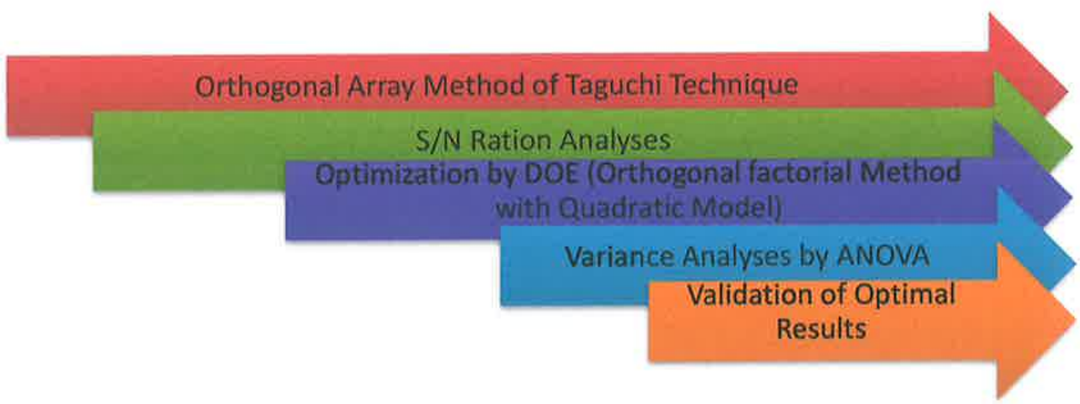


Figure 34 Design methodology used for SAW optimization

Orthogonal Factorial Method (OFM) is an experiment which involves more than one randomized factors. Factorial method consider possible values or "levels", and take on all possible combinations of these levels across all such factors. Taguchi orthogonal arrays are effective for factorial design. Factorial design simply identify the significant factors.

Factors are quantitative (Numerical numbers) and the quadratic model contains the linear terms (A), the interaction terms (AB) and the quadratic terms (AA).

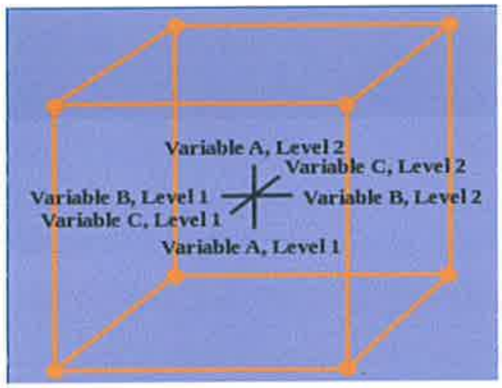


Figure 35 Methodology of Orthogonal factorial method (OFM)

For this study four weld parameters (continuous controllable factors) of interest are selected which are current (amp), voltage (v), travel speed (mm/min) and heat input (KJ/mm) as mentioned in Table 16. The factors can be classified as either continuous or categorical but we've assigned Continuous factors instead of categorical type with minimum and maximum value because SAW's factors values may change while welding. Whereas our responses (analyzed on mean value) are ultimate tensile strength (MPa), weld hardness (VHR), deposition rate (mm), reinforcement (mm) and bead width (mm) as mentioned in Table 17. Each response is also assigned with minimum and maximum values and our aim is to maximize the mean of weld strength, deposition rate, bead width, reinforcement and to minimize mean of hardness.

Table 16 Factors for experiment

Name	Units	Type	Role	Low	High
A:Current	Amp	Continuous	Controllable	470.0	760.0
B:Voltage	Volts	Continuous	Controllable	26.0	30.0
C:Travel Speed	mm/Min	Continuous	Controllable	455.0	818.0
D:Heat Input	KJ/mm	Continuous	Controllable	1.17	2.92

Table 17 Responses to be measured

Name	Units	Analyze	Goal	Impact	Sensitivity	Low	High
UTS (Y1)	MPA	Mean	Maximize	3.0	Medium	490.0	600.0
Hardness (Y2)	VHR	Mean	Minimize	3.0	Medium	160.0	205.0
Deposition Rate (Y3)	Kg/Hr.	Mean	Maximize	3.0	Medium	9.0	13.0
Reinforcement Height (Y4)	mm	Mean	Minimize	3.0	Medium	2.0	4.0
Bead Width (Y5)	mm	Mean	Minimize	3.0	Medium	8.0	14.0

5.3.2 EXPERIMENT SET UP FOR S/N RATIO ANALYSES

Experimental layout of S/N ratio analyses is consist of L12 orthogonal array as shown in Table 18 for S/N ratio analyses. Four important variables (A,B,C,D, refer Table 16) given in Table 16 are selected with two levels of each factor and five responses (Y1,Y2,Y3,Y4,Y5, refer Table 17) as shown in Table 17.

Table 18 SAW L12 orthogonal arrays responses Data for experiment

Exp. Run	UTS, Y1	Hardness, Y2	Deposition rate,Y3	Reinforcement Height,Y4	Bead Width, Y5
L1	522	161	9	4	10
L2	536.4	201	9	2	10
L3	571	176	12	3	12
L4	586	203.5	11	4	12
L5	542	193	10	3	11
L6	524	177	9	4	10
L7	592	184.6	11	3	12
L8	565	203.5	13	4	12
L9	522	167	10	4	11
L10	563	168	11	2	8
L11	538	201	10	2	9
L12	585	205	13	4	12

S/N ratio for each level of process variable is computed for analyses where higher value of S/N ratio related to better quality characteristics. Therefore optimal value was that having highest S/N ratio. S/N ratio for each response and ranking of variables based on difference is calculated and is given in Tables 19 and 20. Formulas largest the best and smallest the best used for these calculations are already given in equation 5.1 and 5.2 in section 5.2.2. From Table 19 and 20 we can see S/N ratio of factors and effect on responses from ranking of each factor.

After ranking and from Table 19 for responses like reinforcement height and bead width, Voltage and travel speed have major impact because travel speed along with voltage which controls deposition will control reinforcement height and bead width. Actually when voltage increases it increase bead width but decrease its height but increase in current only increases the bead height.

For hardness we can see from factors rank current and heat input along with travel speed. This is because current and heat input along with travel speed controls the temperature of weldment and HAZ which results high or low hardness of the weld and HAZ. Ranking of factors in Table 20 is given for other responses like tensile strength and deposition rate. We can say voltage, current and travel speed have major impact. This is because current and voltage affect weld quality by controlling metal transfer, penetration, spatter control, post weld cleaning and by influencing metallurgical and mechanical properties. Similarly these factors along with travel speed control the deposition rate.

Table 19 SN Ratio of responses for SN-S and ranking of factors

Y1$^{`2}$	Y2$^{`2}$	Y3$^{`2}$	Y4$^{`2}$	Y5$^{`2}$	SN-S	Factors	Current, A	Voltage, B	Travel Speed, C	Heat Input, D
272484	25921	81	16	100	-47.7612271	**low**	-48.0002	-48.26	-48.2344	-48.2242
287724.96	40401	81	4	100	-48.1731538	**High**	-48.6847	-48.4248	-48.4505	-48.4607
326041	30976	144	9	144	-48.5408003	**Delta**	0.684446	0.16479	0.216057	0.23651
343396	41412.25	121	16	144	-48.8659139	**Rank**	2	4	3	1
293764	37249	100	9	121	-48.211767					
274576	31329	81	16	100	-47.8689616					
350464	34077.16	121	9	144	-48.8628217					
319225	41412.25	169	16	144	-48.5849659					
272484	27889	100	16	121	-47.7903342					
316969	28224	121	4	64	-48.393297					
289444	40401	100	4	81	-48.1958342					
342225	42025	169	16	144	-48.8601556					

Table 20 SN Ratio of responses for SN-L and ranking of factors

1/y1$^{\wedge 2}$	1/y2$^{\wedge 2}$	1/y3$^{\wedge 2}$	1/y4$^{\wedge 2}$	1/y5$^{\wedge 2}$	SUM	SN-L	Factor	Current, A	Voltage, B	Travel speed, C	Heat Input, D
3.6699E-06	3.8579E-05	0.0123	0.0625	0.01	0.084888	2.14230	low	1.7509	1.805	2.128	1.765
3.4755E-06	2.4752E-05	0.01234	0.25	0.01	0.272374	1.12966	high	1.9062	1.852	1.529	1.892
3.0671E-06	3.2283E-05	0.00694	0.111	0.006944	0.125035	1.80593	Delta	0.1553	0.047	0.598	0.127
2.9121E-06	2.4147E-05	0.00826	0.0625	0.006944	0.077736	2.21875	Rank	3	4	2	1
3.4041E-06	2.6846E-05	0.01	0.111	0.008264	0.129406	1.77609					
3.642E-06	3.1919E-05	0.01234	0.0625	0.01	0.084881	2.14237					
2.8534E-06	2.9345E-05	0.00826	0.111	0.006944	0.126352	1.79683					
3.1326E-06	2.4147E-05	0.00591	0.0625	0.006944	0.075389	2.24538					
3.6699E-06	3.5856E-05	0.01	0.0625	0.008264	0.080804	2.1851					
3.1549E-06	3.5431E-05	0.00826	0.25	0.015625	0.273928	1.12472					
3.4549E-06	2.4752E-05	0.01	0.25	0.012346	0.272374	1.12966					
2.9221E-06	2.3795E-05	0.00591	0.0625	0.006944	0.075388	2.24539					

5.3.3 DESIGN OF EXPERIMENT BY OFM

Design of experiment's run and model was established by orthogonal factorial method because Taguchi orthogonal arrays are useful and effective for standard factorial design. Here L16 orthogonal arrays with design type of quadratic model is used for experimentation to study effects of various controllable input factors on responses [76]. From large data point of shop welding 16 arrays of factors with one replica so total 32 experiment runs of factors are selected for experiment as described in Table 21 and shall be utilized for optimization.

Table 21 Selection of Experiment Design

Type of Factors	Design Type	Center point Placement	Design is Randomized	Number of Replicates	Total Runs
Process	Quadratic Model L16 (4^5)	Random	Yes	1	32

To fit the results of the experiment, the Quadratic model of factors interaction is used and below Table 22 is the statistical data collected from large data points of shop welding. In SAW shop ASME SA516 Gr. 70 (fine grain Normalized plate of 32~34mm thickness) material is used for each run of welding with single bevel angle by using SAW machine of model ESAB LEF-1001 PEK (Refer Annexure 5 for SAW WPS). Whereas response values for each run are measured and taken from actual testing performed in Mechanical test Lab. Weld Joint design and geometry is given below in Fig. 36.

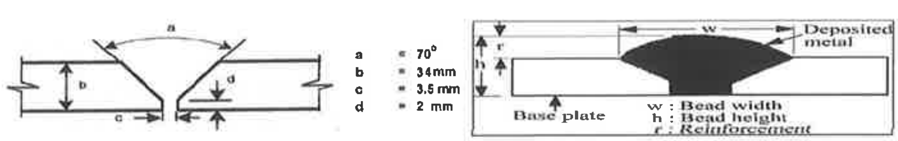


Figure 36 Joint Detail and Weld Geometry [Refer to Annexure-5 for WPS used in welding]

The larger pool of shop data for SAW Welding process is reported in Raw Data file by authors on researchgate "Field Data for GTAW and SAW Welding variables and responses for process optimization Studies" [77] [78].

Table 22 SAW data for experiment

	Factors				Responses				
Sr. No.	**Current**	**Voltage**	**Travel Speed**	**Heat Input**	**UTS**	**Hardness**	**Deposition Rate**	**Reinforcement Height**	**Bead Width**
	(Amp) F1	**(Volts) F2**	**(mm/Min) F3**	**(KJ/mm) F4**	**(MPA) R1**	**(VHR) R2**	**(Kg/Hr.) R3**	**(mm) R4**	**(mm) R5**
1	470	27	576	1.75	537.0	184.0	9	3	11
2	470	29	697	2.34	538.0	198.0	9	3	11
3	660	26	697	2.92	558.0	205.0	0	3	9
4	720	26	818	1.75	594.0	187.0	12	2	9
5	570	27	455	2.92	558.0	205.0	10	4	8
6	570	30	697	1.75	585.0	191.0	10	3	11
7	570	26	576	2.34	560.0	200.5	10	3	8
8	470	30	818	2.92	536.4	201.0	9	2	10
9	720	27	697	1.17	571.0	176.0	12	3	9
10	660	27	818	2.34	555.0	181.0	11	2	8
11	570	29	818	1.17	563.0	162.0	10	2	8
12	720	30	455	2.34	598.5	193.0	13	4	11
13	660	30	576	1.17	557.0	176.0	12	3	12
14	720	28	576	2.92	571.0	172.0	12	3	11
15	470	26	455	1.17	522.0	161.0	9	4	10
16	660	29	455	1.75	519.0	167.0	11	4	12
17	660	27	818	2.34	523.0	178.0	11	2	8
18	660	30	576	1.17	546.0	196.0	11	3	11
19	570	28	818	1.17	537.0	169.0	12	2	9
20	720	26	818	1.75	563.0	168.0	11	2	8
21	720	30	455	2.34	585.0	203.5	13	4	12

22	570	26	576	2.34	548.0	177.0	10	3	9
23	470	27	576	1.75	558.5	165.0	9	3	9
24	570	28	455	2.92	563.0	187.5	10	4	10
25	720	29	576	2.92	579.0	202.5	11	3	10
26	720	27	697	1.17	583.0	200.0	11	3	12
27	660	29	455	1.75	596.0	201.0	10	4	11
28	570	30	697	1.75	597.0	193.0	9	3	11
29	470	29	697	2.34	543.0	173.0	8	3	9
30	660	26	697	2.92	555.0	175.5	10	2	8
31	470	30	818	2.92	585.0	163.0	10	4	12
32	470	26	455	1.17	598.4	161.0	9	4	11

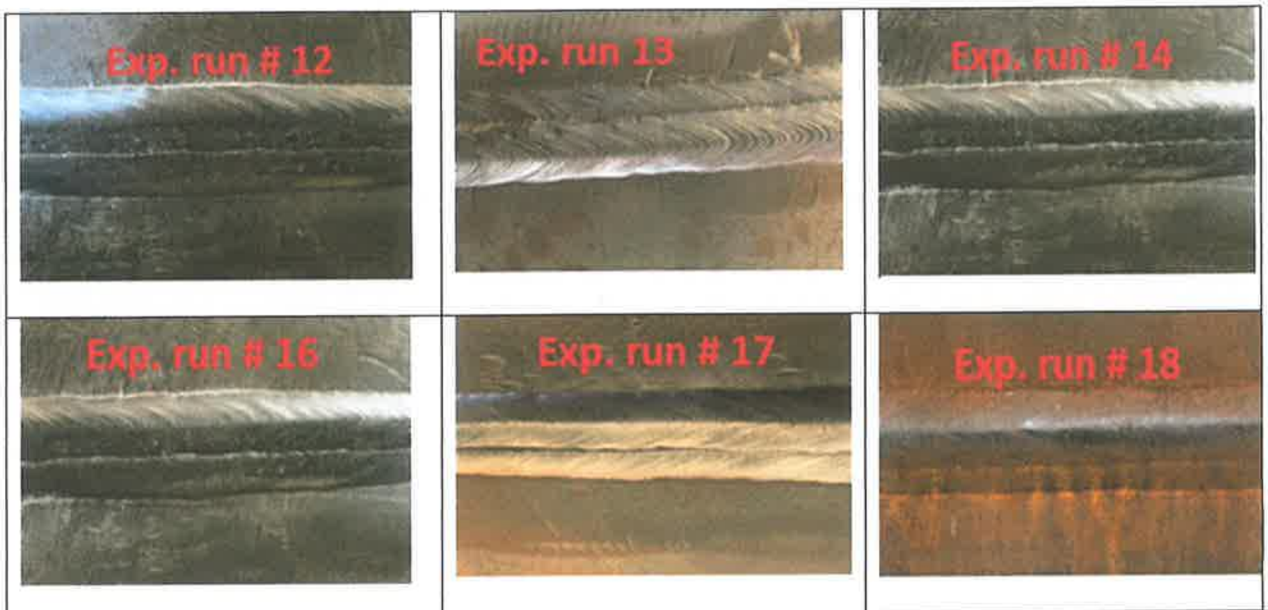


Figure 37 some typical final weld seams of SAW welds resulted from experiment run [Image Magnification 2X]

5.3.4 VARIANCE ANALYSES BY ANOVA

The variance's analysis is performed by ANOVA [72] was conducted to investigate the controllable factor's influences on measured responses then the standardized Pareto chart is drawn for each response with respect to significant factors.

Table 23 Variance analyses for UTS

UTS	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Current	367.79811	1	367.79811	0.67	0.4239
B:Voltage	286.289	1	286.289	0.52	0.4796
C:Travel Speed	572.90164	1	572.90164	1.04	0.5207
D:Heat Input	21.59451	1	21.59451	0.04	0.8451
AA	142.02643	1	142.02643	0.26	0.6173
AB	416.39124	1	416.39124	0.76	0.3954
AC	22.062456	1	22.062456	0.04	0.8434
AD	239.16685	1	239.16685	0.44	0.5177
BB	2296.1168	1	2296.1168	4.18	0.0490
BC	9.245	1	9.245	0.02	0.8982
BD	571.75469	1	571.75469	1.04	0.3211
CC	359.7419	1	359.7419	0.65	0.5289
CD	1439.8383	1	1439.8383	2.62	0.4728
Total error	9887.3883	18	549.29935		
Total (corr.)	16979.775	31			

R-sq. = 41.769615 %, Std. Error of Est. = 23.437136, Mean absolute error = 13.323266

The analyses of variance are calculated for each response and is explained below in Table 23 for tensile strength, Table 24 for weld hardness, Table 25 for deposition rate, Table 26 for reinforcement height and Table 27 for bead width.

ANOVA Table 23 shows variability in tensile strength values by considering each factor separately as well as their interactions. The statistical significance can be obtained by comparing mean square with estimated experimental error. If P-Value is less than 0.05 (α=5%) then then those factors and their interaction are significant in these analyses whereas Value of R-Squared is calculated to explain the fitted in term of variability in the model. All P values less than 0.05 are highlighted in red in Table 23. From this table we can say Voltage has significant effect on tensile strength. This is because arc voltage also governs arc length beneath the flux layer and any change in arc length will change weld metal composition due to change in element. By changing the composition mechanical properties will also change. R-squared value shows model is fitted 41.7% of variability in tensile strength. Similarly standard error is 23.43 and mean absolute error is 13.32. Significance of R-squared, standard error and mean absolute error already explained in section 5.2.4.

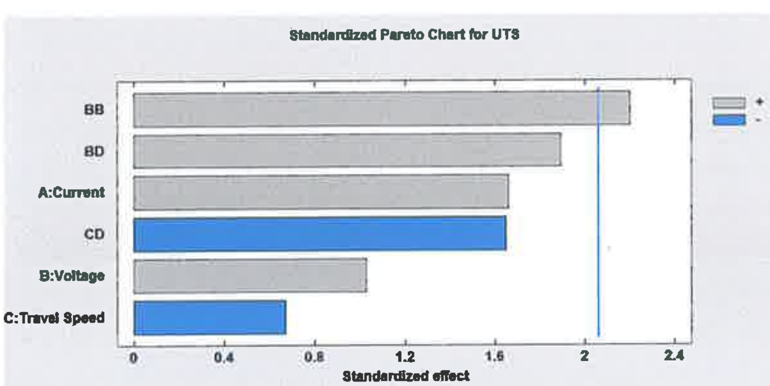


Figure 38 Standard Pareto Chart for Tensile Strength

Variance analyses through ANOVA significant factor is identified and then plotted against the standardize effect. From Pareto chart in Fig. 38, we can say interaction of voltage (BB) has significant effect on ultimate tensile strength whereas the other factors can be ignored. Although factors having p value up to 0.05 are of our interest however other factors and their interactions have alsao an (indirect) effect on tensile strength. Therefore effect of those factors are also plotted on this chart by considering cut off value for p is 0.5.

Table 24 Variance analyses for hardness

Hardness	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Current	5.9511087	1	5.9511087	0.03	0.5623
B:Voltage	93.732954	1	93.732954	0.42	0.5959
C:Travel Speed	66.217445	1	66.217445	0.30	0.5133
D:Heat Input	570.12904	1	570.12904	2.54	0.0128
AA	78.789368	1	78.789368	0.35	0.5605
AB	10.963231	1	10.963231	0.05	0.8274
AC	17.569888	1	17.569888	0.08	0.7826
AD	299.20902	1	299.20902	1.34	0.2629
BB	98.401184	1	98.401184	0.44	0.5859
BC	70.507813	1	70.507813	0.31	0.5817
BD	45.923904	1	45.923904	0.20	0.6561
CC	227.35054	1	227.35054	1.01	0.5371
CD	123.61509	1	123.61509	0.55	0.5772
Total error	4032.4428	18	224.0246		
Total (corr.)	6948.7422	31			

R-sq. = 41.968737 %, R-sq. (adjusted for d.f.) = 0.05727 %, Std. Error of Est. = 14.967451
Mean absolute error = 9.6759945

ANOVA Table 24 shows variability in hardness values by considering each factor separately as well as their interactions. If P-Value is less than 0.05 then then those factors and their interaction are significant in these analyses. All P values less than 0.05 are highlighted in red in Table 24. From this table we can say heat input values (D) has significant effect on tensile strength. Although P values for voltage (B) and current (A) are more than 0.05 but difference is very less with 0.05 but heat input formula includes both current and voltage in direct proportions. R-squared value shows model is fitted 41.96% of variability in hardness. Similarly standard error is 14.96 and mean absolute error is 9.67. This is also obvious from below standardized Pareto chart which is drawn for hardness. Fig. 39 is showing effect of not only significant factors but also effect of other factors having indirect effect on hardness by considering cut off value of p is 0.5.

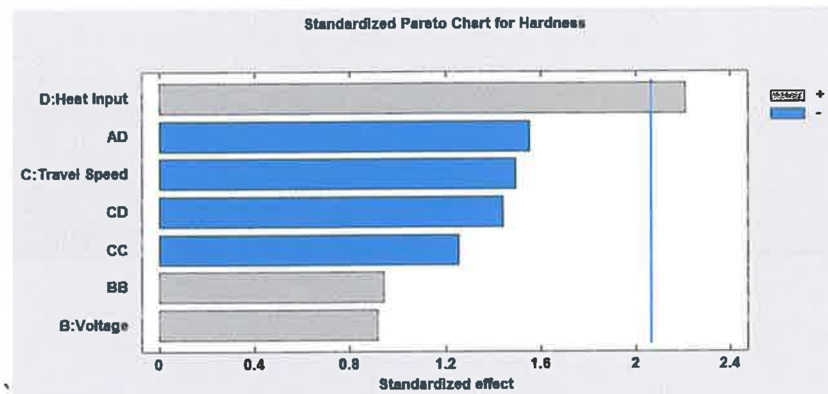


Figure 39 Standard Pareto Chart for Weld Hardness

Table 25 Variance analyses for deposition rate

Deposition Rate	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
A:Current	10.032731	1	10.032731	25.74	0.0010
B:Voltage	0.0022547676	1	0.0022547676	0.01	0.9402
C:Travel Speed	1.4553648	1	1.4553648	3.73	0.0392
D:Heat Input	0.0097730667	1	0.0097730667	0.03	0.8759
AA	0.54949426	1	0.54949426	1.41	0.2595
AB	1.9461324	1	1.9461324	4.99	0.0384
AC	0.23537443	1	0.23537443	0.60	0.4472
AD	0.54498377	1	0.54498377	1.40	0.2524
BB	0.4614682	1	0.4614682	1.18	0.2909
BC	0.28125	1	0.28125	0.72	0.4068
BD	0.61141311	1	0.61141311	1.57	0.2264
CC	1.7840806	1	1.7840806	4.58	0.0463
CD	0.2045451	1	0.2045451	0.52	0.4781
Total error	7.0152434	18	0.38973574		
Total (corr.)	49.96875	31			

R-sq. = 85.960739 %, R-sq. (adjusted for d.f.) = 75.821272 %, Std. Error of Est. = 0.62428819
Mean absolute error = 0.38166919

ANOVA Table 25 shows variability in deposition rate values by considering each factor separately as well as their interactions. If P-Value is less than 0.05 then then those factors and their interaction are significant in these analyses. All P values less than 0.05 are shown in Table 25. From table we can say current (A), current-voltage (AB) interaction and travel speed interaction (CC) values has significant effect on deposition rate. Standardized Pareto chart is drawn for deposition rate with cut off value of p is 0.25. Therefore this Fig. 40 is showing effect of all those factors and their interactions having cut off value up to 2.5.

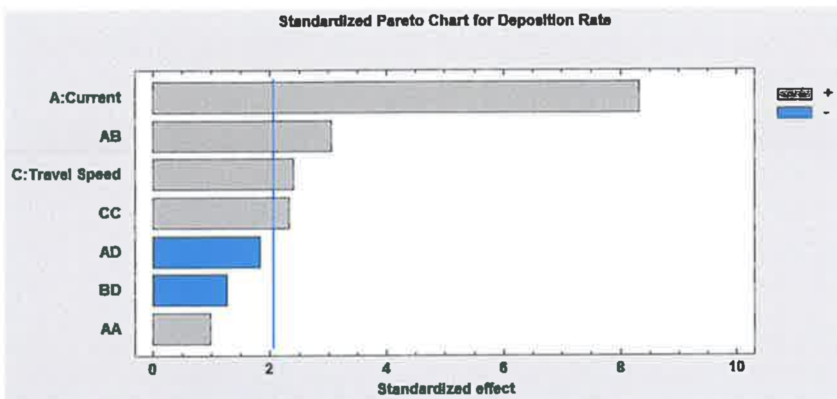


Figure 40 Standard Pareto Chart for Deposition Rate

Table 26 Variance analyses for reinforcement height

Reinforcement Height	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
A:Current	0.00012351814	1	0.00012351814	0.00	0.9785
B:Voltage	0.046386845	1	0.046386845	0.28	0.6029
C:Travel Speed	4.3041191	1	4.3041191	26.02	0.0010
D:Heat Input	0.00059923573	1	0.00059923573	0.00	0.9527
AA	0.001445091	1	0.001445091	0.01	0.9266
AB	0.070502348	1	0.070502348	0.43	0.5221
AC	0.0094413698	1	0.0094413698	0.06	0.8139
AD	0.12264797	1	0.12264797	0.74	0.4005
BB	0.014866504	1	0.014866504	0.09	0.7678
BC	0.03125	1	0.03125	0.19	0.5690
BD	0.043478283	1	0.043478283	0.26	0.6144
CC	0.01426888	1	0.01426888	0.09	0.7723
CD	0.0056818195	1	0.0056818195	0.03	0.8550
Total error	2.9773519	18	0.16540844		
Total (corr.)	16.96875	31			

R-sq. = 82.453912 %, R-sq. (adjusted for d.f.) = 69.781737 %, Std. Error of Est. = 0.40670436
Mean absolute error = 0.18886106

In analyses of variance Table 26 for reinforcement we have found that travel speed (C) has significant effect on reinforcement (p=0.0001). Travel speed affect penetration and low/high travel speed also affect reinforcement height. Pareto chart is drawn as below in Fig. 41 to show effect of all those factors and their interactions having p-value of up to 0.5 (cut off value is 2.5).

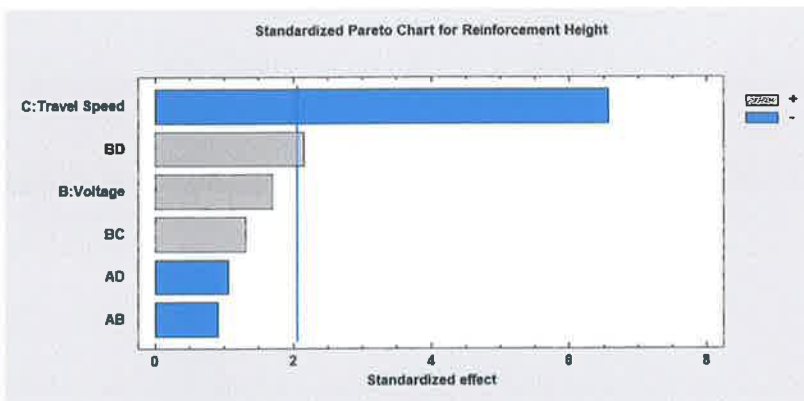


Figure 41 Standard Pareto Chart for Reinforcement

Table 27 Variance analyses for bead width

Bead Width	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Current	0.75148203	1	0.75148203	0.78	0.6895
B:Voltage	4.4292589	1	4.4292589	4.62	0.0010
C:Travel Speed	7.7084418	1	7.7084418	8.04	0.0454
D:Heat Input	2.3158664	1	2.3158664	2.42	0.1375
AA	0.15932076	1	0.15932076	0.17	0.6883
AB	1.4821264	1	1.4821264	1.55	0.7296
AC	0.088440018	1	0.088440018	0.09	0.7648
AD	0.067948089	1	0.067948089	0.07	0.7931
BB	0.043689327	1	0.043689327	0.05	0.8333
BC	0.125	1	0.125	0.13	0.7222
BD	0.024456542	1	0.024456542	0.03	0.8749
CC	0.27169826	1	0.27169826	0.28	0.6909
CD	2.5056816	1	2.5056816	2.61	0.1233
Total error	17.249855	18	0.95832529		
Total (corr.)	63.875	31			

R-sq. = 72.994356 %, R-sq. (adjusted for d.f.) = 53.49028 %, Std. Error of Est. = 0.9789409
Mean absolute error = 0.63458189

In analyses of variance Table 27 for bead width we have found that voltage (B) and travel speed (C) have significant effect on Bead width. Open circuit/welding arc voltages and travel speed are critical variables in any SAW process affecting bead shape. However Pareto chart as shown below in Fig. 42 is drawn with cut off of p is 0.25 to show effect of significant factors as well as other factors having indirect effect.

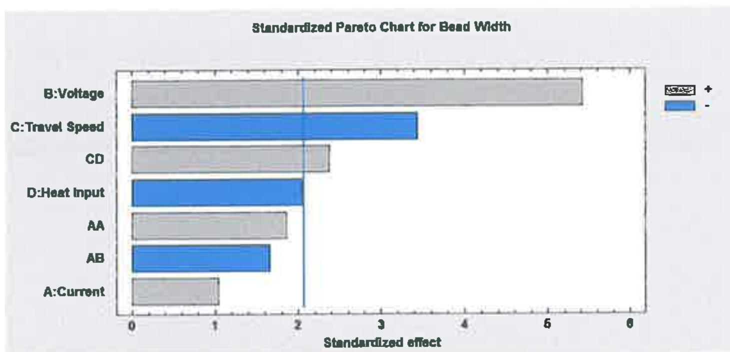


Figure 42 Standard Pareto Chart for Bead Width

5.3.5 OPTIMIZATION BY DESIRABILITY ANALYSES

Optimum factors setting values are obtained through optimized desirability which is obtained by considering combined result of all five responses for specific predicted values. For optimization of response values we have selected confident level of 95%. Whereas predicted values of each response is a mean value of upper 95% and lower 95% limit. For the calculated results of all responses desirability is calculated for each response per each run of experiment which is called observed desirability. Whereas based on lower and upper 95% limits predicted desirability is calculated for each response. Then mean of all these is taken as optimized desirability.

For this study we have selected desirability function methodology as explained in section 5.2.5 because practically for multi response optimization this technique is widely used [73].

Table 28 shows all calculation where responses are optimized by getting their prediction by taking mean of lower 95% limits and upper 95% limits. Here optimized predicted values for UTS, hardness, deposition rate, bead width and reinforcement are 555.18, 170.63, 12.99, 2.07 and 9.10 respectively. Whereas based on Derringer and Suich's desirability function as defined above the calculated desirability for UTS, hardness, deposition rate, bead width and reinforcement are 0.59, 0.76, 0.99, 0.96 and 0.81 respectively.

The overall desirability or optimized desirability is equals 81.2%, and this is calculated by using stat graphics centurion XVII software [72] as follow; took desirability of each response then raised it to power of its impact then results are multiplied together and again raised the product power to one and divided the answer with sum of all impacts. The result is always a number between zero and one, more weight is given to response having higher impact. This is how an overall desirability for any process solution is calculated using equation 5.7 to make sure that all responses are predicted (Table 28) to be within desired limits which is in our case is 0.812. Here D is overall desirability of each response and D* is overall process desirability and is geometric means of overall desirabilities D.

Table 28 Optimal response values

Response	Optimized	Prediction	Lower 95.0% Limit	Upper 95.0% Limit	Desirability (D)
UTS	yes	555.18	473.02	637.34	0.59
Weld Hardness	yes	170.64	118.17	223.10	0.76
Deposition Rate	yes	12.98	10.81	15.18	0.99
Reinforcement Height	yes	2.07	0.65	3.50	0.96
Bead Width	yes	9.12	5.67	12.53	0.82

Optimized desirability, D* = 0.81283308

Optimized settings of factors are obtained based on optimized desirability vs optimized responses values and are given in Table 29 and graphical representation is shown in Figs. 43.

Table 29 Optimal factors values

Factor	Setting
Current	630.90 amp
Voltage	29.93 volts
Travel Speed	817.99 mm/Min
Heat Input	1.17 KJ/mm

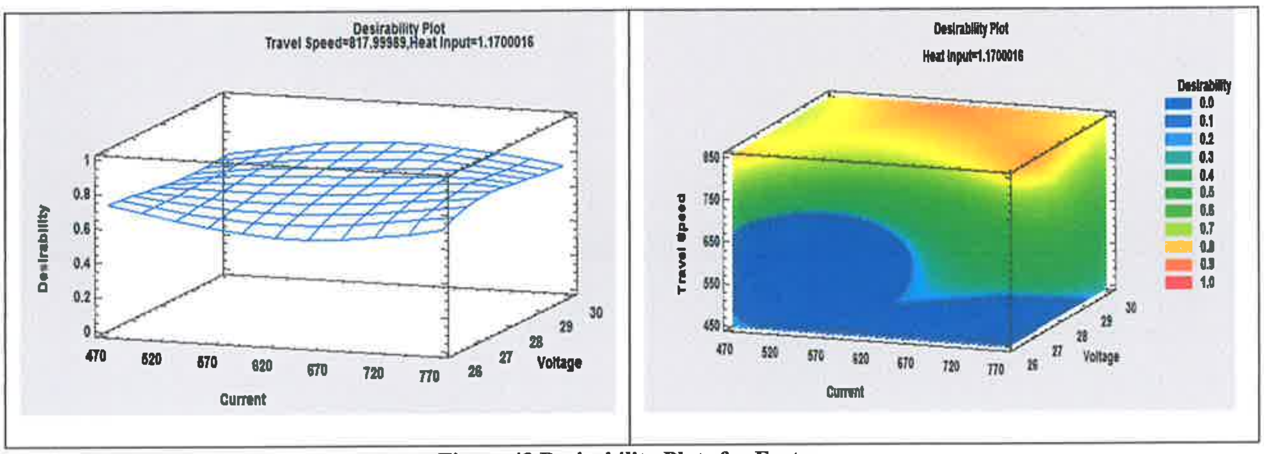


Figure 43 Desirability Plots for Factors

Optimization results based on desirabilities (D) 3D plots [72] for the overall desirability D* (0.813) function which already explained in above are drawn along with color plot for variations in desirability for overall process in Fig. 43.

CHAPTER 6

RESULTS AND CONCLUSIONS

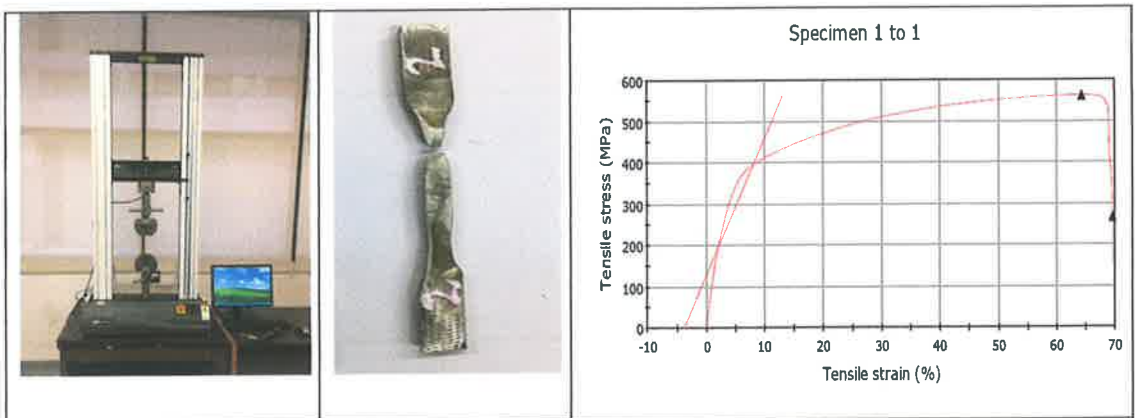
In the previous chapter optimum values of GTAW and SAW process parameters are determined by using various statistical tools. Finally confirmation runs of welds were welded to ascertain the optimization results.

6.1 VALIDATION OF GTAW OPTIMIZATION RESULTS

After getting the optimal values for factors next stage was to validate these values. In order to do this final weld run was conducted by using these optimal values obtained during these analyses. Welding was performed under same circumstances using the same material. Final results of UTS, hardness, micro/macro structure were obtained and found very close to the optimal responses as mentioned in Table 30. Final confirmation welding and samples taken for testing are shown in Fig. 44.

Figure 44 Confirmation run and samples taken for testing

Tensile testing was performed by using UTS machine of Instron-model 3367. Actual response value of UTS is found 561.78 MPa as compare to optimal value which obtained from desirability analyses was 562.891 MPa. Tensile test results are shown below Table 30 and TS machine, broken sample and graph are shown in below fig. 45.



	Maximum Load (kN)	Tensile Strength (MPa)	Elongation (%)	Modulus (MPa)
1	26.74	561.78	69.51	3318.68
Min	26.74	561.78	69.51	3318.68
Mean	26.74	561.78	69.51	3318.68
Max	26.74	561.78	69.51	3318.68

Figure 45 Tensile test machine, Sample and Graph

Hardness testing was performed by using vicker hardness tester of Buehler USA, model Micromet-3 advance. Actual hardness values observed 72~74HRB whereas optimal value was 71.365 HRB. Hardness tester model and sample used are shown in fig. 46.

Figure 46 Hardness tester and sample

Three samples were taken for GTAW process in order to find base metal, HAZ and weld metal hardness. Standard location of hardness testing for these three locations are shown in Fig. 47. In final results only weld metal hardness was included where average value of weld metal hardness readings was considered i-e 73.048 HRB.

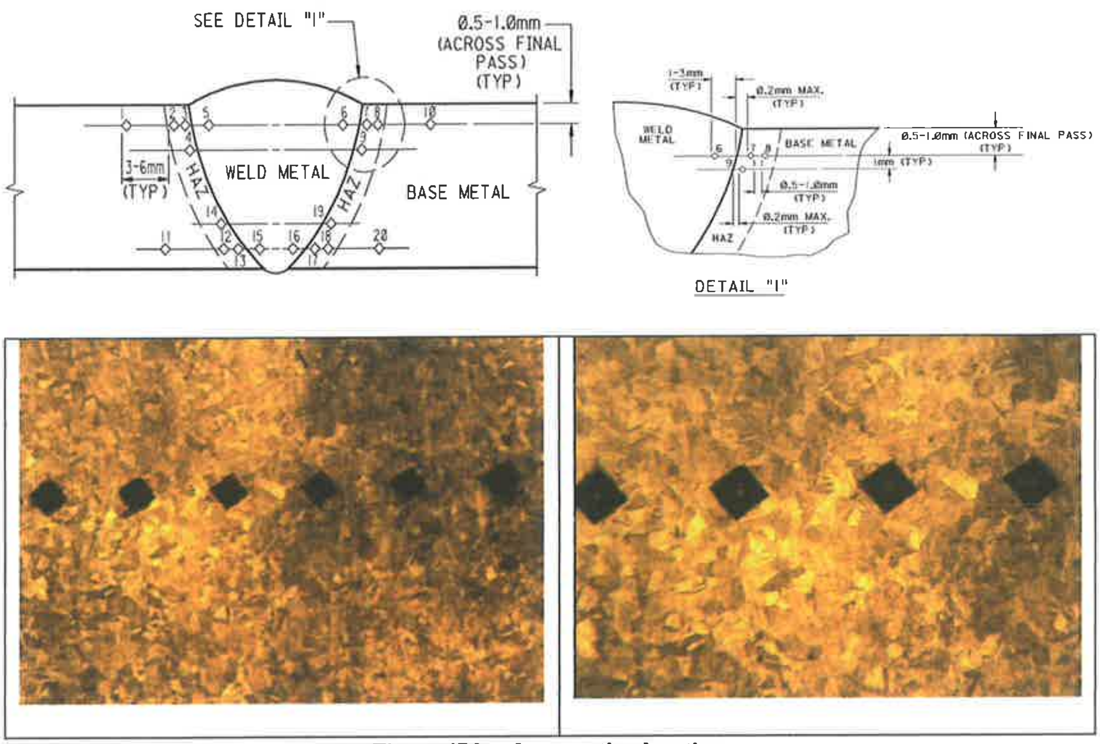


Figure 47 hardness testing locations

Ametek brand spectrometer was used to find the chemical composition of weld metal which is found as follow as shown in Fig. 48.

Type		C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
		%	%	%	%	%	%	%	%	%	%
<x>		0.0118	0.430	1.82	0.0035	< 0.00050	18.61	2.46	11.38	0.0033	0.0851
Type		Cu	Nb	Ti	V	W	Pb	Sn	As	Ca	Sb
		%	%	%	%	%	%	%	%	%	%
<x>		0.111	< 0.0040	0.0066	0.0308	0.0137	< 0.0020	0.0089	< 0.0015	0.00039	< 0.0020
Type		Se	Ta	B	N	Fe					
		%	%	%	%	%					
<x>		< 0.0020	< 0.0200	0.00069	0.0728	64.9					

Figure 48 Spectrometer and chemical composition reading

Carbon contents plays important role to produce carbides which caused sensitization in stainless steel and maximum allowed 0.030% for this grade and here found within range. Similarly Cr (18-20%) which is added for corrosion resistance also in range. Ni (8-12%) is added to reduce thermal and electrical conductivity is also in range. Other alloying elements are also in range therefore weldment have desired chemical composition. Although after welding there is minor change in composition which is due to addition of filler metal but all elements are within the range. Ferrite number for austenitic steel remains between 5-20. This number shows delta ferrite and it is essential to restrict delta ferrite because this cause the material to become magnetic and susceptible to hot cracking. Heat input calculated for optimal values by using equation 2.11 is 0.761KJ/mm with current 150 Amp, Voltage 11 volts and travel speed 130 mm/min. This is also acceptable because it does not exceed the maximum heat input used in applicable WPS.

Microstructure of final weld, HAZ and base metal was also observed by using optical microscope of brand Zeiss, model-axioplan 2 Imaging. Microscope used and microstructures observed are shown in Fig. 49.

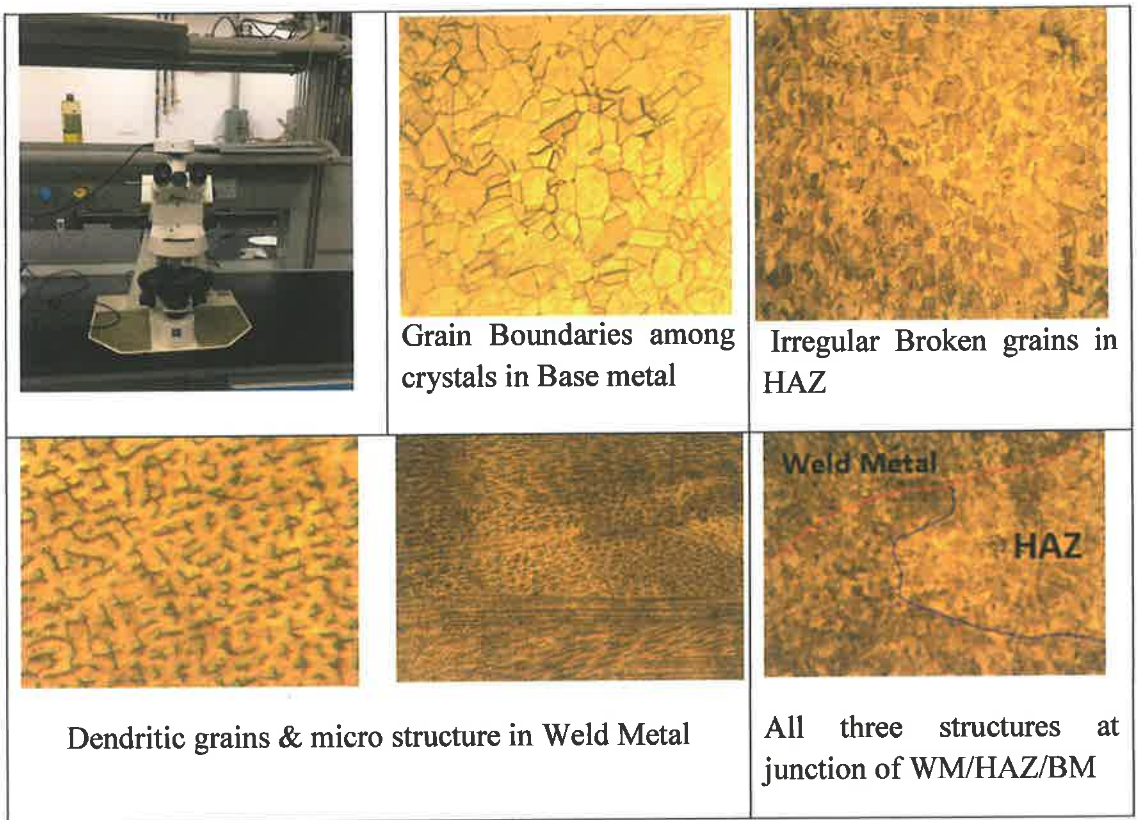


Figure 49 Microstructures of base, weld and HAZ area [Image Magnification 100X]

As there is no or little heat effect on base metal other than of weld metal and HAZ area therefore fine austenitic grain crystalline structure was observed for solution annealed stainless steel base material. In HAZ irregular and broken austenitic grains were observed due to temperature changes during welding and then suddenly cooling in air. But in weld metal area dendritic austenitic grains observed due to melting of base metal and addition of filler with subsequent cooling to form new structure which changes weld metal composition and micro structure as compared to base metal.

In order to check the quality of weld Macro examination was also performed. Here for examination one cross section of the weldment was polished and then etched by using etchant of Aqua rega ($HNO3$ + HCL in ratio of 1:3 respectively). This test was performed to find any possible porosity, lack of penetration and side wall fusion and weld profile and mainly hot weld cracks or sensitization due to formation of carbides precipitates. Macrograph is shown in below Fig. 50 and examination was performed at less than 20x magnification.

Figure 50 Macrograph Examination of final weld (GTAW)

Now final optimal results obtained from Taguchi analyses, desirability analyses and obtained from actual testing are summarized in Table 30. From this table we can say results are very close to each other by using both techniques. As per ASME Sec IX base metal qualification range and WPS used (refer annexure-4) these analyses can be used for 5mm-21.5mm base metal thickness.

Table 30 Comparison between optimized and actual results (GTAW)

Optimized Factors By Desirability Function	Optimized Response values Desirability Function	Taguchi array of factors giving desire results	Desire Results by Taguchi SN Analyses	Actual Results (Responses)
Current = 145 amp	UTS = 562.89 MPa	Current 150 amp	UTS 564 MPa	UTS = 561.78 MPa
Gas Flow Rate = 12 L/Min	Hardness = 70.43 HRB	GFR 12 L/Min	Hardness 72.66	Hardness = 73.048
Travel Speed = 90 mm/Min		Travel speed 95 mm/Min		

From these analyses we can conclude that for hardness gas flow rate has major effect along with travelling speed whereas current has least impact. Because low gas flow rate cause porosity and very high gas flow rate cause to increase brittleness. Then very high/low travelling speed cause sudden increase and decrease in the temperature of weld joint and HAZ which results high hardness which is not desirable. Similarly for tensile strength current and gas flow rate have major impact whereas travel speed has the least. This is because current along with proper gas flow rate affect weld quality by controlling metal transfer, penetration, spatter control, post weld cleaning and by influencing metallurgical and mechanical properties.

6.2 VALIDATION OF SAW OPTIMIZATION RESULTS

After getting the optimal values for factors next stage was to validate these values. In order to do this final weld run was conducted by using these optimal values obtained during these analyses. Welding was performed under same circumstances using the same material. Final results were obtained and found very close to the optimal responses as mentioned in Table 30. Here hardness testing was performed by using Wilson Hardness 432SVD machine where optimal value was 170.6 whereas in actual it was found around 167. The hardness machine and final seam are shown in Fig. 51.

Figure 51 Final weld seam, Hardness machine and sample

Three samples were taken for hardness testing in base metal, HAZ and weld metal. Test locations are already described in section 6.1 fig 45. Here only average of weld metal hardness values is considered i-e 167.30. Actual test sample and locations are shown in fig 52.

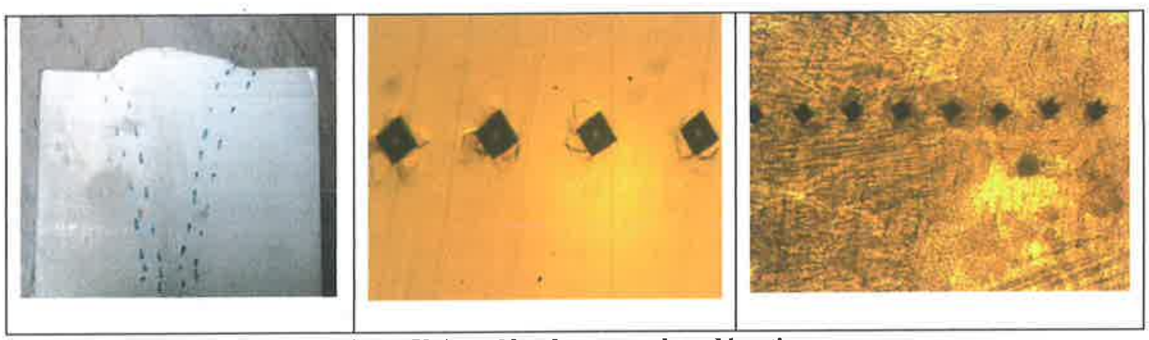


Figure 52 Actual hardness sample and locations

Tensile testing was performed by using UTS machine of Galdabini model Sun60-V630 and test sample as shown in Fig. 53. Here optimal value of UTS was 555 MPa whereas in actual it was found 559 MPa. Reinforcement was measured by using Cambridge type welding gauge and found 2.5 whereas bead width with simple ruler and found around 9~10mm. Calculated heat input using equation 2.11 is 1.3KJ/mm with actual parameters of 630 amp, 30 volts and 820 mm/Min traveling speed. These analyses can be used for maximum thickness of base metal.

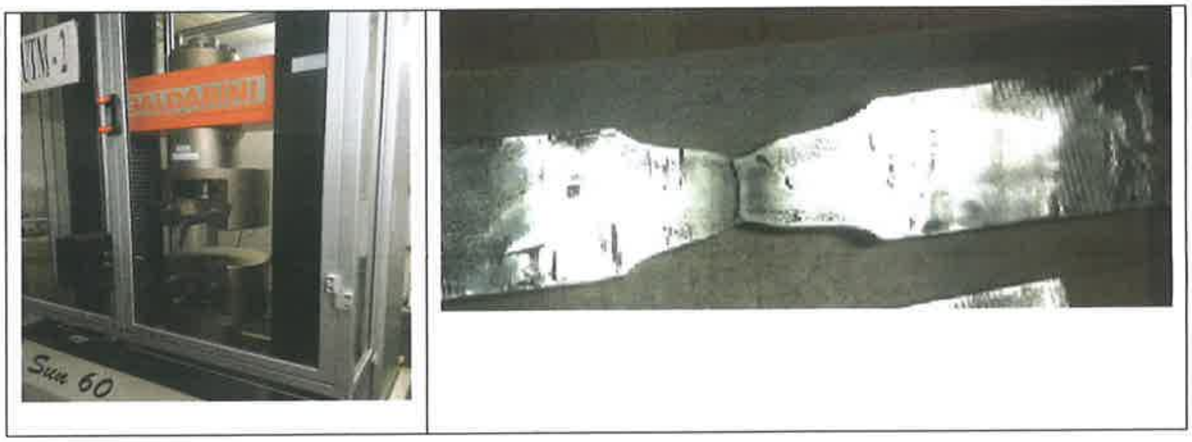


Figure 53 Tensile test machine and sample

Table 31 Comparison between optimized and actual results (SAW)

Optimized Factors	Optimized Responses	Actual Results (Responses)
Current = 630.90 amp	UTS = 555.18 MPa	UTS = 558.50 MPa
Voltage = 29.93 volts	Hardness = 170.64	Hardness = 167.30
Travel Speed = 817.99 mm/Min	Deposition rate = 12.98 Kg/Hr.	Deposition rate = 12.5 Kg/Hr.
Heat Input = 1.17 KJ/mm	Reinforcement = 2.07 mm	Reinforcement = 2.5 mm
	Bead Width = 9.12 mm	Bead Width = 9~10 mm

Above Table 31 shows a comparison between optimal values calculated and actual values obtained from actual run. Effect of all factors in desirability analyses is also found in align with the ranking of factors which was calculated by using S/N analyses.

After these analyses we can conclude that for responses like reinforcement height and bead width Voltage and travel speed have major impact because travel speed along with voltage which controls deposition will control reinforcement height and bead width. Actually when voltage increases it increase bead width but decrease its height but increase in current only increases the bead height. For hardness heat input along with travel speed. This is because current and heat input along with travel speed controls the temperature of weldment and HAZ which results high or low hardness of the weld and HAZ.

For other responses like tensile strength and deposition rate we can say voltage, current and travel speed play an important role. This is because current and voltage affect weld quality by controlling metal transfer, penetration, spatter control, post weld cleaning and by influencing metallurgical and mechanical properties. Similarly these factors along with travel speed also control the deposition rate.

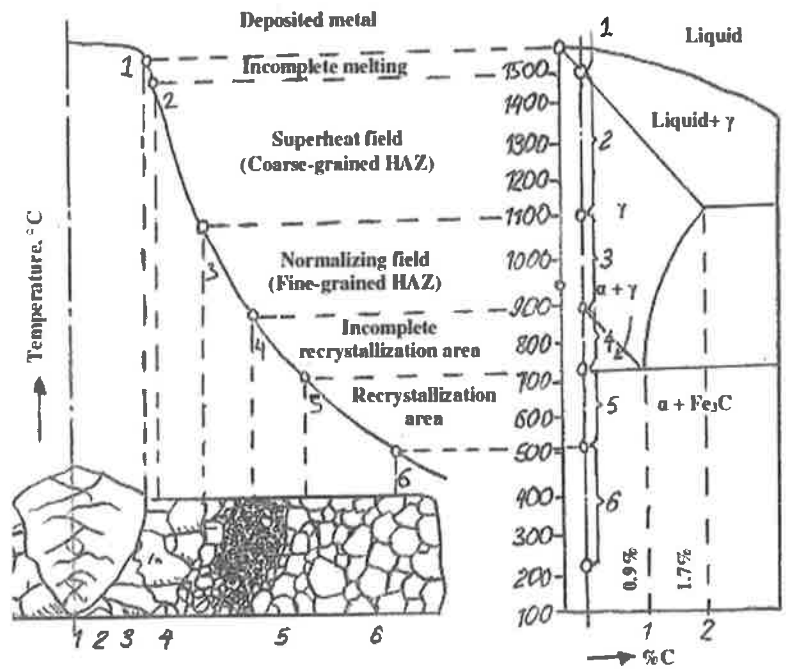


Figure 54 Schematic representation of the microstructures at different temperatures [79]

Due to high heat and current above structure as shown in fig. 54 is normally observed in SAW welding [79]. There is one portion of parent metal which remains unaffected from temperature during welding and therefore no change in structure. HAZ has three different microstructures that include course grain zone, fine grain zone and transition zone. Coarse grains are produced due to high rate of heat input with more time spending above coarse grain temperature. Maximum size will be near the weld fusion line and decrease with distance from that line. Hardness also depends upon this and varies. Normally it declines from weld interface to coarse grain zone. Thermal cycles alter the microstructure of HAZ. Fine grain structure region reached that temperature where complete recrystallization or grain refinement occurs. In transition zone only partial transformation occurs. In fusion zone parent metal melts and mixes with filler and causes cast structure of coarse columnar grains which is actually deposited weld metal. This columnar structure is due to cooling of weld joint from parent metal towards weld metal center. In short we can say final weld metal structure depends upon heat input and cooling rate and therefore structure can be take any form based on these factors.

Macrograph of final weld is shown in below Fig. 55 and examination was performed at less than 20x magnification. No imperfection visible as shown below.

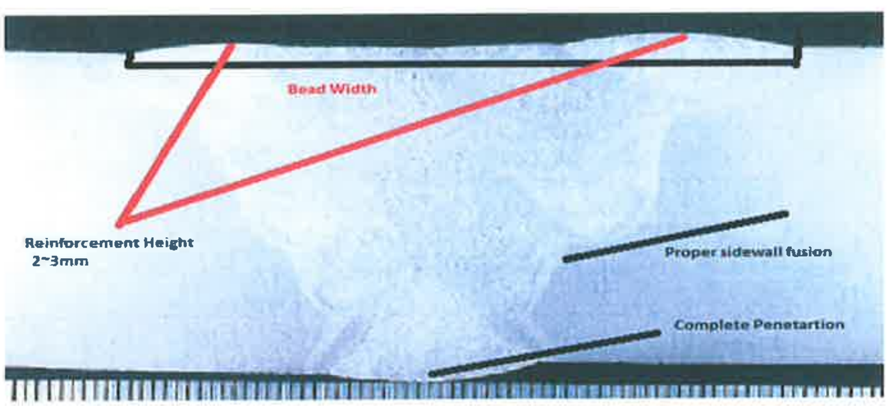


Figure 55 Macrograph Examination of final weld (SAW)

6.3 RESULTS AND CONCLUSIONS

This study discloses the useful and effective combination of different advance statistical tools like application of Taguchi orthogonal array method, desirability function and central composition design of Regression analyses for optimizing of GTAW process parameters and orthogonal factorial method and desirability analyses for optimization of submerged arc welding (SAW) process in order to enhance weld quality. By using these methodologies optimal values for selected controllable factors and responses are found, confirmed and validated by performing actual runs of weld and then comparing the actual results with the calculated optimal values. These welds are found defect free with desire mechanical properties and having best weld quality. Therefore we can say this strategy of optimization by using these different statistical tools is proved to be successful. We can not only find the main effect but also quadratic as well as interaction effects in the model. Hence conclusion can be made that for given certain material and similar welding circumstances these analyses can be used for the best quality weld.

Conclusion of this research work can be summarized as follow:

- Study highlighted the important role of standards and welding best practices deployed in contemporary welding world. And described GTAW and SAW process and various controlling variables as well as Standards compliant tolerance zone on these variables Acceptable window of Welding Process parameters selection which apparently give good quality welds).
- Study provides a framework of exploring the best combination of conditions which provide Highest Quality (or Enhanced Quality) Weld by optimizing within this standard based acceptable zone of welding conditions. This constrained optimization is essentially multi criteria optimization. The statistical tools used for this purpose in Studying GTAW and SAW processes are Design of Experiments (DOE) through Signal over Noise (S/N) ratio and Desirability Function (DF)

analyses to further narrowing down the optimum region for process parameters settings within welding standard based recommended search space.

- The above framework of the analyses can be applied for any such welding case and can be combined in a single software package to find optimal the weld conditions leading to enhanced weld quality.

APPENDIX – 1

Ferrous Metals Classification

<table>
<tr><td rowspan="10">Ferrous Metals</td><td rowspan="3">Carbon steel</td><td rowspan="3">C less than 1%, Mn less than 1.65% & C, Si less than .60%, weldability depends upon Carbon contents</td><td>Low Carbon Steel</td><td>0.10 to 0.25% C, 0.25 to 1.5% Mn, widely used & easily weld able by any process</td></tr>
<tr><td>Medium Carbon Steel</td><td>0.25 to 0.50% C, 0.60 to 1.65% Mn, readily weld able by any process with proper preheat</td></tr>
<tr><td>High Carbon Steel</td><td>0.50 to 1.03% C, 0.30 to 1% Mn, readily weld able by any process with proper preheat/PWHT</td></tr>
<tr><td rowspan="2">Alloy Steel</td><td>Low Alloy Steel</td><td colspan="2">Mn more than 1.65%, Si & Cu more than 0.60% & mini 3.99% of Co, Cb, Mo, Ni, Ti, W, V or Zr , easily weld able if base metal receive proper preheat and weldment proper PWHT</td></tr>
<tr><td>High Alloy Steel</td><td colspan="2">More % age values of alloying elements, Pitting resistance equivalent is used which is = %Cr+3.3%Mo+16%N, AWS A4.2 & ASTM E562 are used to find Ferrite contents</td></tr>
<tr><td rowspan="5">Stainless Steel</td><td rowspan="5">Contains 11-30% Cr, Low melting temperature & thermal conductivity and higher coefficient of thermal expansion with good corrosion resistance</td><td>Austenite</td><td>Mostly used with excellent corrosion resistance, weldability & ductility with good high T oxidation resistance but susceptible to Pitting & Chloride SCC</td></tr>
<tr><td>Martensitic</td><td>C up to 0.35%, Cr 11.5 to 18%, Magnet & High hardness so welding require preheat/PWHT, susceptible to HIC during welding, used for cutlery & surgical instruments</td></tr>
<tr><td>Ferritic</td><td>11.5 to 30% Cr, Magnet & non harden able by heat treatment limited weldability due to low HAZ toughness, susceptible to embrittlement, used for heat exchanger tubes</td></tr>
<tr><td>Duplex</td><td>Combine effect of ferrite & Austenite phases, resistance to chloride SCC & SSC, High strength, good toughness and ductility</td></tr>
<tr><td>Precipitation Hardened</td><td>High strength and Mo, Ti, Cd, Al are used as precipitation hardening promotors, Few types are non-weld able but some are which don't require Preheating</td></tr>
</table>

APPENDIX – 2

Preheat Temperature

P-Number	ASME Section I	ASME Section VIII	ASME B31.1	ASME B31.3
1 (Mild Carbon Steels)	175°F for C > 0.3% and t > 1". Otherwise 50°F	175°F for C > 0.3% and t > 1". Otherwise 50°F	175°F for C > 0.3% and t > 1". Otherwise 50°F	50°F for t < 1" and T_s = 71 ksi. 175°F for t = 1" or T_s > 71 ksi
3 (Low Alloy Steels)	175°F for T_s > 70 ksi or t > 5/8". Otherwise 50°F	175°F for T_s > 70 ksi or t > 5/8". Otherwise 50°F	175°F for T_s > 60 ksi or t > 1/2". Otherwise 50°F	50°F for t < 1/2" and T_s = 71 ksi. 175°F for t = 1/2" or T_s > 71 ksi
4 (1-1/4 Chromemoly Steels)	250°F for T_s > 60 ksi or t > 1/2". Otherwise 50°F	250°F for T_s > 60 ksi or t > 1/2". Otherwise 50°F	250°F for T_s > 60 ksi or t > 1/2". Otherwise 50°F	300°F for all thicknesses and T_s
5 (2-1/4 Chromemoly Steels)	400°F for T_s > 60 ksi or C_r > 6.0% and t > 1/2". Otherwise 300°F	400°F for T_s > 60 ksi or C_r > 6.0% and t > 1/2". Otherwise 300°F	400°F for T_s > 60 ksi or C_r > 6.0% and t > 1/2". Otherwise 300°F	350°F for all thicknesses and T_s
8 (Stainless Steel	None	None	50°F	50°F

Post Weld Heat Treatment Temperature

P#	ASME Section I	ASME Section VIII	ASME B31.1	ASME B31.3
1	1,100°F for t > 3/4"	1,100°F for t > 1-1/2" or 1-1/4" < t < 1-1/2" and T_p < 200°F	1,100°F to 1,200°F for t > 3/4"	1,100°F to 1,300°F for t > 3/4"
3	1,100°F for t > 5/8" and C > 0.25%	1,100F for all Group No. 3 materials. Otherwise 1,100°F for t > 1/2" and C > 0.25%	1,100°F to 1,200°F for t > 5/8" and C > 0-.25%	1,100°F to 1,200°F for t > 3/4" or T_s > 71 ksi
4	1,100°F for O.D. > 4" or C > 0.15% or T_p < 250°F	1,100°F for O.D. > 4" or t > 5/8" or C > 0.15% or T_p < 250°F	1,300°F to 1,375°F for NPS > 4" or t > 1/2" or C > 0.15" or T_p < 250°F	1,300°F to 1,375°F for t > 1/2" or T_s > 71 ksi
5	1,250°F for C_r > 3.0% or O.D. >" or t > 5.8" or C > 0.15% or T_p < 300°F	1,250°F for C_r > 3.0% or O.D. > 4" or t > 5.8" or C > 0,15% or T_p > 300°F	1,300F to 1,400°F for NPS > 4" or t > 1/2" or C_r > 3.0% or C > 0.15% or T_p < 300°F	1,300°F to 1,400°F for t > 1.2" or C_r > 3.0% or C > 0.15%

APPENDIX – 3

Essential/Non-Essential/Suppl. Essential Variables for SAW/GTAW[61]

Variables	Brief of Variables	Essential	Suppl. Essential	Non Essential	Applicable Welding Processes
Weld Joint	Groove Design			X	GTAW, SAW
	Backing			X	GTAW, SAW
	Root Spacing			X	GTAW, SAW
Base Material	Group Number		X		GTAW, SAW
	T limits		X		GTAW, SAW
	T Qualified	X			GTAW, SAW
	P Number	X			GTAW, SAW
	t Pass	X			GTAW, SAW
Filler Metal	F Number	X			GTAW, SAW
	A Number	X			GTAW, SAW
	Diameter			X	GMAW, FCAW, SAW
	Flux/Wire Class				SAW
	Suppl.& Alloy elements	X			SAW
	Alloy Flux	X			SAW
	Flux product form	X			GTAW
	Flux designation			X	SAW
	Filler	X			GTAW
	Thickness t	X			GTAW, SAW
	Classification		X	X	GTAW, SAW
	Flux & Recrushed slag	X			SAW
	Flux/Wire Class		X	X	SAW
welding Position	Position		X	X	GTAW, SAW
	Vertical up/down			X	GTAW
Preheat	Decrease more than 100F	X			GTAW, SAW
	Increase more than 100F		X		GTAW, SAW
PWHT	PWHT	X			GTAW, SAW
	PWHT Temp. & Time		X		GTAW, SAW
	T limits	X			GTAW, SAW
Electrical Characteristics	Heat Input		X		GTAW, SAW
	Current/polarity		X		GTAW, SAW
	Tungsten Electrode			X	GTAW
Gas	Trail or composition			X	GTAW

	Single/Mixture or %age	X			GTAW
	Flow Rate			X	GTAW
	Backing flow			X	GTAW
	Backing or Composition	X			GTAW
	Shielding/Trailing	X			GTAW
Technique	String/Weave			X	GTAW, SAW
	method of Cleaning			X	GTAW, SAW
	method back gouge			X	GTAW, SAW
	Oscillation			X	GTAW, SAW
	Multi/Single Pass vice versa		X		GTAW, SAW
	Manual/Automatic			X	GTAW, SAW
	Peening			X	GTAW, SAW
	Thermal Processes	X			GTAW, SAW

APPENDIX – 4

Welding Procedure Specification for Gas Tungsten Arc Welding

Welding Process(es) : GTAW

Type(s) : MANUAL (Automatic,Manual,Machine Or Semiautomatic)

CODES : ASME SEC. IX

JOINTS (QW - 402)

Joint Design : As Per Drawings & Appropriate Welding Description — Root Spacing : As Per Drawings

Backing : Without Backing — Retainers : None

BASE METALS (QW - 403)

P NO. 8	Group No.	1	TO	P.No. 8		Group No. 1
Specification Type & Grade:		SA 312 TP 316L	SA 312 TP 316 L	or	Similar	
Thickness ranges qualified for:						
Base Metal :	Groove	5 mm to 21.48 mm		Fillet:	All Sizes and Thickness	
Diameter Range Qualified:						

FILLER METALS (QW - 404)	GTAW
Spec. No. (SFA)	5.9
AWS No. (Class)	ER 316 L
F.No.	6
A - No.	8
Size of Filler Metals	2 mm & 2.4 mm
Weld Metal Thickness Range:	6 mm (Max)
Filler metal addition or deletion	Filler metal added
Flux addition or deletion	Flux not used
Fillerb metal product form	Solid
Filler metal brand name	Any
Cosumable insert	None

POSITIONS (QW - 405)		POST WELD HEAT TREATMENT (QW - 407)	
Position(s) of Groove:	All	Temperature Range:	: N/A
Welding Progression:	Uphill for vertical	Time Range:	: N/A
Position(s) of Fillet:	All	Heating Rate:	: N/A
		Cooling Rate:	: N/A

PREHEAT (QW - 406)

Preheat Temp. (min):	:16°C
Interpass Temp (max):	:175°C
Preheat Maintenance:	None

GAS (QW - 408)

	Gas(es)	Percent Composition (Mixture)	Flow Rate
Shielding	Argon	99.99%	18-22CFH
Trailing	N/A	N/A	N/A
Backing	Argon	99.99%	12-15CFH

TECHNIQUE (QW - 410)			
String or Weave bead :	String & Weave	Oscillation:	N/A
Max. Weave Width :(SMAW)	3 X core wire dia.	Contact tube to work distance:	N/A
Orifice / Gas cup size :	5,8 mm	Multiple/Single pass (per side) :	Multiple
Initial Cleaning:	SS Grinding / SS Brushing	Multiple/Single Electrode(s) :	N/A
Method of back gauging:	N/A	Travel Speed :	See table below
Other :	N/A	Peening:	Slag Removal is not a Peening.

ELECTRICAL CHARACTERISTICS (QW - 409)			
Current (A.C./D.C.) :	DC	Polarity	DCEN
Amps (Range) :	90-135	Volts (Range):	See table below
Tungsten Electrode Size & Type:	2 & 2 .4mm x EWTh2	Mode of Metal Transfer for GMAW:	N/A
Pulsing current:	None	(Spray arc, short circutting arc, etc.)	
Electrode / Wire Feed Speed Range:	N/A		

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia	Current Type Polarity	Current Amps	Volts (Range)	Speed mm/min	Heat Input KJ/mm
1st Pass	GTAW	ER316 L	2 mm	DCEN	90-120	8-13	60-110	0.85
2nd Pass	GTAW	ER316 L	2 mm	DCEN	95-135	8-13	75-135	0.722
Rest	GTAW	ER316 L	2.4 mm	DCEN	100 -150	8-13	90-135	0.78

LEGEND: N/A - Not Applicable

APPENDIX – 5

Welding Procedure Specification for Submerged Arc Welding

Type(s) : Machine	(Automatic, Manual, Machine or Semi Auto)	
CODES : ASME SEC. IX'		Date: 6-Mar-03

JOINTS (QW - 402)	
Joint Design : As Per Drawing & Appropriate weld description	Root Spacing : As per Drawing
Backing : Base metal	Retainers : None

BASE METALS (QW - 403)						
P.No. 1	Group No 1 & 2		TO	P.No. 1		Group No.1 & 2
Specification Type & Grade	SA 516 Gr.70/60 /SA36			Any Similar Metal		
Thickness ranges qualified for:						
Base Metal :	Groove	: 5 to 32 mm				
Diameter Range Qualified: N/A						

FILLER METALS (QW - 404)	SAW
Spec. No. (SFA)	5.17
AWS No. (Class)	EH 12 K - F7A8
F.No.	6
A - No.	1
Size of Filler Metals	3.2 mm
Weld Metal Thickness Range: Groove	32 mm Max
Fillet :	ALL
Weld Pass Thickness	< 12 mm
Electrode - Flux (Class)	OK Flux 10.62 (ESAB)
Flux and / or electrode name	OK Autorod 12.32 (ESAB)
Consumable Insert	None
Recurshed slag	Not used

POSITIONS (QW - 405)	**POST WELD HEAT TREATMENT (QW - 407)**
Position(s) of Groove: 2G	Temperature Range: N/A
Welding Progression: Horizontal	Time Range: N/A
Position(s) of Fillet.	Heating Rate: N/A Cooling Rate: N/A

PREHEAT (QW - 406)	**GAS (QW - 408)**				
Preheat Temp. (min): 20°C			Percent Composition		
Interpass Temp (max): 250°C			Gas(es)	(Mixture)	Flow Rate
Preheat Maintenance: None	Shielding	-	N/A	N/A	N/A
	Trailing	-	N/A	N/A	N/A
	Backing	-	None	N/A	N/A

TECHNIQUE (QW - 410)	
String or Weave bead : String	Oscillation: N/A
Max. Weave Width : 7x Wire size used	Contact tube to work distance: 25 to 30 mm
Orifice / Gas cup size : N/A	Multiple/Single pass (per side) : Multiple
Initial Cleaning: Grinding/Wire Brush/Hand Tool	Multiple/Single Electrode(s) : Single
Method of back gouging: Grinding / Arc Air	Speed : See Table Below
Other : NIL	Peening: Slag removal is not peening

ELECTRICAL CHARACTERISTICS (QW - 409)	
Current (A.C /D.C) : DC	Polarity: DCRP
Amps (Range) : See Table Below	volts (Range): See Table Below
Tungsten Electrode Size & Type: N/A	Mode of Metal Transfer for GMAW: N/A
Pulsing current: None	(Spray arc, short circuiting arc, etc.)
Electrode / Wire Feed Speed Range: N/A	

Weld Layer(s)	Process	Filler Metal		Current		Volts (Range)	Speed mm / min.	Heat Input (AV) KJ/mm
		Class	Dia	Type Polarity	Amps			
Root Pass	SAW	EH12K	3.2mm	DCRP	400-600	25-30	500-600	1.5
Hot Pass	SAW	EH12K	3.2mm	DCRP	400-600	25-30	500-600	1.5
Fill	SAW	EH12K	3.2mm	DCRP	400-700	25-32	600-700	1.315
Cap	SAW	EH12K	3.2mm	DCRP	400-700	25-32	650-700	1.315
Back Weld	SAW	EH12K	3.2mm	DCRP	400-600	25-32	650-700	1.315

REFERENCES

[1] [Online]. Available: http://www.weldinghistory.org/whfolder/folder/wh1900.

[2] "Welding handbook, welding processes Part 1," *Miami Florida: American Welding Society 2004.* ISBN 0-87171-729-8

[3] "Specification for Welding Shielding Gases," *Approved by the American National Standards Institute*, 8, 1997 ANSI / AWS A5.32/A5.32M - 97 (R2007).

[4] [Online]. Available: http://www.pendarvismanufacturing.com/tig-welding.php

[5] M. H. William, "Gas tungsten arc welding handbook" *Tinley Park, Illinois: Good heart–Will cox Company*. ISBN 1-56637-206-2

[6] [Online]. Available: http://nptel.ac.in/courses/112107144/welding/lecture10.htm

[7][Online].Available: http://www.thefabricator.com/article/tubepipefabrication/ electro slag- cladding-for-repair-or-buildup-provides-viable-alternative

[8] A. Pillai, "Some investigation on the Interaction of the Process Parameters of Submerged Arc welding", *Manufacturing Technology and Research (An International Journal)*, Vol. 3No.1and2, June-July

[9][Online]. Available:https://mechanical-engg.com/gallery/image/2589-SAW-processjpg

[10] M. Jou, "Experimental study and modeling of GTA welding process." *Journal of Manufacturing Science and Engineering*, 2003. 125: p. 801-808.

[11] A. K. Srirangan, S. Paulraj, "Multi-response optimization of process parameters for TIG welding of Incoloy 800HT by Taguchi grey relational analysis," *Eng. Sci. Technol.* 19 (2016) 811–817

[12] Y. S. Yegaie, A. Kermanpur, M. Shamanian, "Numerical simulation and experimental investigation of temperature and residual stresses in GTAW with a heat sink process of Monel 400 plates", *Journal of Materials Processing Technology* Volume 210, Issue 13, 1 October 2010, Pages 1690-1701

[13] K. S. Pujari, D. V. Patil, M. Gurunath, "Selection of GTAW process parameters and optimization the weld pool geometry for AA 7075-T6 Al alloy", *materials today,* Volume 5, Issue 11, Part 3, 2018, Pages 25045-25055

[14] S. C. Bodkhe, D. R. Dolas, "Optimization of Activated Tungsten Inert Gas Welding of 304L Austenitic Stainless Steel", *Procedia Manufacturing,* Volume 20, 2018, Pages 277-282

[15] H. K. Bhadeshia, L.E. Svensson, "The microstructure of submerged arc weld deposits for high strength steels," *Journal of Materials Science*, 1989. 24: p. 3180-3188.

[16] J. Bauer, "Microstructure and properties of thermomechanical controlled processing steels for linepipe applications," *Ironmaking and Steelmaking,* 2005. 32(4): p. 325-330.

[17] R. W. Fonda, G.Spanos, "Microstructural evolution in ultralow Carbon steel weldments - Part 1, Controlled thermal cycling and continuous cooling transformation diagram of the Weld Metal" *Metallurgical and Materials Transactions*, 2000. 31 A: p. 2145-2153.

[18] S. P. Lu, "Microstructure and wear property of Fe-Mn-Cr-Mo-V alloy cladding by submerged arc welding," *Journal of Materials Processing Technology*, 2004. 147: p. 191-196.

[19] H. Sieurin, "Austenitic reformation in the heat affected zone of duplex stainless steel 2205" *Materials Science and Engineering*, 2006. 1 418: p. 205-256.

[20] D. Wojnowski, Y. K. Oh, J. E. Indacochea, "Metallurgical assessment of the softened HAZ region during multipass welding," *Journal of Manufacturing Science and Engineering,* 2000. 122: p. 310-315.

[21] M. Eroglu, M. Akosy, N. Orhan, "Effect of coarse initial grain size on microstructure and mechanical properties of weld metal and HAZ of a low carbon steel," *Material Science and Engineering*, 1999. A(269): p. 59-66.

[22] C. S. Chai, T. W. Eagar, "The effect of SAW parameters on weld metal chemistry" *Welding Research Supplement*, 1980: p. 93s-98s.

[23] V. Gunaraj, N. Murugan, "Prediction of Heat Affected Zone characteristics in Submerged Arc Welding of structural steel pipes," *Welding Journal,* 2002: p. 94s-98s.

[24] P. Yayla, E. Kaluc, and L. K. Ural, Effects of welding processes on the mechanical properties of HY 80 steel weldments. Materials and Design, 2006: p. Article in Press.

[25] R. R. Dhas, S. Kumanan, "optimization of parameters of submerged arc weld using non-conventional techniques", Available: https://doi.org/10.1016/j.asoc.2011.05.041

[26] S. Choudhary, R. Shandely, A. Kumar, "Optimization of agglomerated fluxes in submerged arc welding", Available: https://doi.org/10.1016/j.matpr.2017.12.083

[27] M. A. Moradpour, S. H. Hashemi, K. Khalili, "Multi-objective Optimization of Welding Parameters in Submerged Arc Welding of API X65 Steel Plates," *Journal of Iron and Steel Research, International* Volume 22, Issue 9, September 2015, Pages 870-878

[28] A. Biswas, A. Bhowmik, "Study of Heat Generation and Its Effect During Submerged Arc Welding (SAW) on Mild Steel Plate at Zero Degree Celsius Plate Temperature", *Materials today*: Volume 5, Issue 5, Part 2, 2018, Pages 13400-13405

[29] M. Satheesh, J. Edwin, S. Kumar, "Modeling and Analysis of Weld Parameters on Micro Hardness in SA 516 Gr. 70 Steel," *Procedia Engineering*, Volume 38, 2012, Pages 4021-4029

[30] A. Choudhary, M. kumar, R. Deepak, "Experimental investigation and optimization of weld bead characteristics during submerged arc welding of AISI 1023 steel", *Defence Technology* Volume 15, Issue 1, February 2019, Pages 72-82

[31] T. H. Mohammed, A. Al-Dwairi, S. F. Obeidat, "Optimization and control of bending distortion of submerged arc welding I-beams", *Journal of Constructional Steel Research* Volume 142, March 2018, Pages 78-85

[32] K. Li, Z. Wu, Y. Zhu, L. Cuirong, "Metal transfer in submerged arc welding", *Journal of Materials Processing Technology* Volume 244, June 2017, Pages 314-319

[33] D. W. Cho, D. Venkata, "Analysis of molten pool behavior by flux-wall guided metal transfer in low-current submerged arc welding process", *International Journal of Heat and Mass Transfer* Volume 110, July 2017, Pages 104-112

[34] D. W Cho, D. Venkata, W. H. Song, "Molten pool behavior in the tandem submerged arc welding process", *Journal of Materials Processing Technology* Volume 214, Issue 11, November 2014, Pages 2233-2247

[35] E. Dhas J. Dhas, "A review on optimization of welding process", *International conference on modeling, optimization and computing, Procedia Engineering* 38 (2012) 544-554

[36] L. Holuba, J. Dunovskýb, K. Kovandac, L. Kolaříkd, "SAW - Narrow Gap Welding CrMoV Heat-Resistant Steels Focusing to the Mechanical Properties Testing" 25th *DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM* 2014, Procedia Engineering 100 (2015) 1640 – 1648

[37] A. Ghosha, S. Chattopadhyayab, R. K. Dasb, P. K. Sarkar, "Prediction of Submerged Arc Welding Yield Parameters through Graphical Technique" *Procedia Engineering* 10 (2011) 2797–2802

[38] P. Schaumann, M. Collmann, "Influence of Weld Defects on the Fatigue Resistance of Thick Steel Plates" *5th Fatigue Design Conference, Fatigue Design 2013 Procedia Engineering* 66 (2013) 62 – 72

[39] A. Deshmukh, V. ketachalam, “Analyses of penetration rates of SAW process on cyclic fatigue life”, *Journal of Constructional Steel Research*, Volume 142, March 2018

[40] N. D. Pandey, A. Bharti, R. S. Gupta, “Effect of submerged arc welding parameters and fluxes on element transfer behavior and weld metal chemistry”, *J Mater Process Technology* 1994; 40:195e211.

[41] H. L. Tsai, Y. L. Tarng, C. M. Tseng, “Optimization of submerged arc welding process parameters in hard facing”, *Int. J Adv. Manuf. Technol.* 1996:402e6.

[42] Y. S. Tarng, W. H. Yang, S.C Juang, “The use of fuzzy logic in the Taguchi method for the optimization of the submerged arc welding process” *Int. J Adv. Manuf. Technol.* 2000:688e94.

[43] L. Vera, B. Othero-de, J. Cornelis, V. Herman, N. Nasareno, B. Ivani, “Effects of a post weld heat treatment on a submerged arc welded ASTM A537 pressure vessel steel”, *ASM International MEPEG* 2001:249e57.

[44] Y. S. Tarng, S. C. Juang, C. H. Chang, “The use of grey-based Taguchi methods to determine submerged arc welding process parameters in hard facing”, *J Mater Process Technol.* 2002; 128: 1e6.

[45] M. Ana, P. Mercado, E. D. Paulino, L .H. Victor, “Chemical and structural characterization of the crystalline phases in agglomerated fluxes for submerged-arc welding” *J Mater Process Technol.* 2003; 141: 93e100.

[46] S. Datta, A. Bandyopadhyay, P.K Pal, “Grey based Taguchi method for optimization of bead geometry in submerged arc bead-on-plate welding”, *Int. J Adv. Manuf. Technol.* 2008; 39: 1136e43

[47] V. Gunaraj, N. Murugun, “Application of response surface methodology for predicting weld bead quality in submerged arc welding of pipes”, *J Mater Process Technol.* 1999; 88: 266e75.

[48] P. K. Pal, S. Datta, “Grey-based taguchi method for optimization of bead geometry in submerged arc bead –on-plate welding”, *J Adv. Manuf. Technol.* 39:1136–1143 (2008)

[49] “Modern Welding Technology. Prentice Hall Inc.”, *Englewood Cliffs, NJ, Howard Cary*, B. (1979)

[50] F. Soul, N. Hamdy, “Numerical simulation of residual stress and strain behavior”, *November 22nd 2011Reviewed: April 27th 2012Published: November 21st* 2012, Available: https://DOI: 10.5772/47745

[51] H. H. Wang, J. Huang, Y. Huang, "Investigation of heat transfer and fluid flow in welding by numerical modeling", *November 2016 Applied Thermal Engineering 113* Available: https://DOI: 10.1016/j.applthermaleng.2016.11.008

[52] W. Wang, "The great minds of carbon equivalent/the evolution of carbon equivalent equations", *materials group, EWI*

[53] [Online]. Available: https://canteach.candu.org/Content%20Library/20053432.pdf

[54] S. Kou. "Welding Metallurgy 2nd edition", *ISBN*: 0-471-43-491-4

[55] "Defects in SAW welding", [Online]. Available: https://www. Canadian metal working.com/article/ fabricating/get-ready- for-more-saw-output

[56] M. Consonni, C. F. Wee, C. Schneider, "Manufacturing of welded joints with realistic defects", *Paper presented at NDT 2011 - 50th annual conference of the British Institute of Non-Destructive Testing*, 13-15 Sept. 2011. Telford, UK

[57] "General welding discontinuities", [Online]. Available: www.nde-ed.org /Education Resources/Community College/ Radiography/Tech Calibrations/

[58] "Causes of weld porosity in GTAW, [Online]. Available:/https://www.weldpedia.com /2014/08/10- causes-of-weld-porosity-and-their-practicable-preventions/

[59] "Common-tig-problrms-and-solutions" [Online]. Available: www.fabricatingand metalworking.com/2011 /09/ 10

[60] S. Maurice, O. T. Lewis. "Fabrication, Welding, and In-Shop Inspection", *Pressure Vessels Field Manual*, 2013.

[61] "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators", *Sec IX, A.S., ASME Boiler and Pressure Vessel Code, ed. T.A.S.O.M. Engineers., New York*

[62] "Specifications of Line Pipe*", Institute, A.P., API 5L* -. 2004

[63] "Preheat and PWHT temperatures", *Sec I, VIII, B31.1 and B31.3, ASME Boiler and Pressure Vessel Code*, ed. *T.A.S.O.M. Engineers., New York*

[64] T. Thulukkanam, "Quality Control and Quality Assurance, Inspection, and Nondestructive Testing", *Dekker Mechanical Engineering*, 2013.

[65] M. Bashiri, M. Shiri, M. H. Bakhtiarifar "A Robust Desirability-based Approached to optimizing Multiple Correlated Responses", ‖ *Journal of industrial engineering and production research*, Vol. 262, (2015), Number 2.

[66] M. Yousefieh , M. Shamanian , A. Arghavan , “Analysis of design of experiments methodology for optimization of pulsed current GTAW process parameters for ultimate tensile strength of UNS S32760 welds”, *Metallogr. Microstruct. Anal.* 1 (2012) 85–91

[67] A. K. Srirangan, S. Paulraj, “Multi-response optimization of process parameters for TIG welding of Incoloy 800HT by Taguchi grey relational analysis”, *Eng. Sci. Technol.* 19 (2016) 811–817

[68] E. Harrington, “The desirability function and quality loss functions”, ‖ *Ind. Qual. Control,* Vol. 12, (1965), PP. 494-498.

[69] J. Faraway, “Practical Regression and ANOVA Using R, first ed.”, *University of Bath, Bath*, 2002 [Online]. Available: http://www.maths.bath.ac.uk/ ~jjf23/book/pra.pdf

[70] “Ferrous Material Specifications Sec II-Part A”, *ASME Boiler and Pressure Vessel Code, ed. T.A.S.O.M. Engineers., New York*

[71] “Regression Analyses, The Minitab Blog”, [Online]. Available: http://blog. minitab. com/blog/ adventures-in-statistics-2/regression-analysis

[72] “Stat graphics Centurion XVII” -[Online]. Available: http://www.statgraphics .com/centurion-xvii

[73] E. Harrington, “The desirability function and quality loss functions”, ‖ *Ind. Qual. Control,* Vol. 12, (1965), PP. 494-498.

[74] C. Douglas, E. Montgomery, “Design and Analysis of Experiments, eighth ed.”, *John Wiley & Sons, Inc, New Jersey*, 2013

[75] J. Faraway, “Practical Regression and ANOVA Using R, first ed.”, *University of Bath, Bath*, 2002 [Online] Available: http://www.maths.bath.ac.uk/ ~jjf23/book/pra.pdf

[76] G. Derringer, “Simultaneous optimization of several response variables”, *Journal of quality technology*, Vol. 12, (1980), PP. 214- 219

[77] “Field data for gas tungsten arc welding GTAW variables and responses for process optimization studies” [Online] Available:/www.researchgate.net/publication/327831226

[78] “Field data for submerged arc welding SAW variables and responses for process optimization studies” [Online] Available: /www.researchgate.net/publication/327831226

[79] A Hall, “Thesis on effect of welding speed on the properties of ASME SA516 Gr 70 Steel”, *Department of Mechanical engineering, University of Saskatchewan, Saskatoon.*

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